

STUDIES IN GEOPHYSICS

Mineral Resources: Genetic Understanding for Practical Applications

Geophysics Study Committee
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Preface

In 1974 the Geophysics Research Board completed a plan, subsequently approved by the Committee on Science and Public Policy of the National Academy of Sciences, for a series of studies to be carried out on various subjects related to geophysics. The Geophysics Study Committee was established to provide guidance in the conduct of the studies.

One purpose of the studies is to provide assessments from the scientific community to aid policymakers in decisions on societal problems that involve geophysics. An important part of such an assessment is an evaluation of the adequacy of present geophysical knowledge and the appropriateness of present research programs to provide information required for those decisions.

This study on *Mineral Resources: Genetic Understanding for Practical Applications* was largely motivated by the scientific and societal questions: How much do we really know about the formation of mineral deposits, and how might expansion of such fundamental knowledge benefit the appraisal of nonfuel resources and the formulation of mineral-resource policy? The thesis of this report is that an improved understanding of the genesis of mineral deposits in various geologic environments is useful for the continued discovery, identification, and evaluation of our nonfuel mineral resources.

The study was developed as a cooperative effort of the Geophysics Study Committee

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and the U.S. National Committee for Geochemistry.* The latter assisted in the selection of the panel, the organization, and the review of the document. The Geophysics Study Committee coordinated the operational and production phases of the panel's activities. The preliminary scientific findings of the panel were presented at a Geological Society of America meeting that took place in Toronto in October 1978. These presentations and the essays contained in this volume provide examples of current basic knowledge of the genesis of nonfuel mineral deposits. They also pose many of the fundamental questions and uncertainties that require additional research. In completing their papers, the authors had the benefit of discussion at this symposium as well as comments of several scientific referees. Responsibility for the individual essays rests with the corresponding authors.

The Overview of the study summarizes the highlights of the essays and formulates conclusions and recommendations. In preparing it, the panel chairman had the benefit of meetings that took place at the symposium, the comments of the panel of authors, and reviews of the U.S. National Committee for Geochemistry and other referees. Responsibility for the Overview rests with the Geophysics Study Committee and the chairman of the panel.

* Members of the U.S. National Committee for Geochemistry are V. Rama Murthy (*Chairman*), Maria Luisa Crawford, Larry W. Finger, Everett A. Jenne, Keith Kvenvolden, Fred T. Mackenzie, Werner J. Raab, William M. Sackett, and Peter J. Wyllie. Previous chairmen were Hubert L. Barnes (1976–1978) and Rosemary J. Vidale (1978–1981).

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Mineral Resources: Genetic Understanding for Practical Applications

Overview and Recommendations

THE CHALLENGE

An adequate and dependable nonfuel mineral supply is fundamental to the economic well-being of our industrial society and to our national security. For 20 of the 32 mineral commodities listed in Table 1, the projected cumulative demand by the year 2000 exceeds our domestic reserves.¹ For only 3 of these commodities does the United States currently produce as much as it consumes. Even on a worldwide basis, reserves of fully half of the commodities will probably be consumed before the year 2020. Significant new discoveries of at least 6 of the 32 commodities must be made before the turn of the century to sustain their projected rate of use. Fortunately, reserve estimates—by their nature—are conservative, and new deposits certainly will be added to our inventory. On a global scale there appear to be adequate reserves to maintain our economy for the remainder of this century, but the United States can depend on these reserves only if international trade will be continued and expanded. The term “remainder of this century” may imply an unwarranted aura of permanence. It is less than 20 years away, and 20 years is a relatively brief period in which to explore for, develop, and bring into production a major mineral deposit. Moreover, we will need not just one but many such deposits. Whether these new discoveries will be sufficient to sustain future demand is by no means clear.

The current situation of mineral-resource supply therefore presents us with a challenge requiring a twofold scientific/technical solution:

Overview and Recommendations

1. *Discovery and utilization* of mineral resources continue to be necessary for our economy, regardless of what particular mineral-resource strategy the country chooses (e.g., conservation, increased production, or stockpiling). We must meet this aspect of the challenge without greatly increasing consumers' costs, energy demands, and environmental degradation; this will require the continual discovery and utilization of high-grade mineral deposits.

2. An *improved assessment* of the magnitude (and location) of resources is necessary for long-range planning and more firmly based policy formulation. Better evaluation of mineral resources would permit gradual technical, economic, and social adaptation to depletion or increased cost of nonrenewable raw materials, through conservation and recycling as well as substitution. In addition, such an assessment is necessary for land-use decisions.² Difficult trade-offs must be faced in deciding the use of public lands in view of the conflicting demands for wilderness and wildlife preservation, resource utilization, urbanization, recreation, and other uses.

Our ability to meet this challenge depends on our successes in locating, identifying, and evaluating mineral deposits. These successes in turn would be enhanced by an improved scientific understanding of the ore-forming processes and the clues they leave in rocks. Geologists need to improve their abilities to deduce, on the basis of fragmentary clues, the probability of hidden resources. Mineral deposits are not accidents of nature but are the products of a series of geological processes. Seemingly similar processes result in ores in one locale and not in others or during only a specific geologic time period; the reasons for this are complex and incompletely understood. Sheldon and Raup (Chapter 8) state "to a new exploration concept, the earth is unexplored." Each new predictive concept, each new exploration technique, or each new type of deposit offers new exploration opportunities.

RESEARCH AND THE AVAILABILITY OF MINERALS

The application of geologic information to the search for ore³ deposits usually takes place through the vehicle of a model, an organized ensemble of factors that characterize the occurrence of a mineral deposit. The model may even point to the location of the deposit. Models bring contributions from many diverse investigations and continually evolve as new information becomes available. Some of this information is genetic, a recognized consequence of the origin or subsequent history of the deposit; the rest is empirical, recognized as significant although the reason for the significance may not be clearly understood. The relevant factors may be definitive or only remotely suggestive; they may be favorable or unfavorable for the location of ore. In no case are *all* the components of a model well known, not even for coal, whose basic genesis is relatively well understood.

An excellent example of a successful model is that for the continental porphyry copper deposits (see Chapter 5), which constitute the major copper resources of the nation and for much of the world. Numerous discoveries in the American Southwest and elsewhere have resulted from recognition of the association of economic mineralization with the following: (1) igneous rocks of a certain composition, texture, and, in Arizona, age; (2) distinctive patterns of mineralization; (3) persistent behavior of the copper, iron, molybdenum, and other elements in the oxidized and leached outcrops; (4) recognizable geophysical signatures; and (5) a systematic zonal pattern of alteration-mineral assemblages in the wall rocks.

An analogous model for porphyry molybdenum deposits was developed through careful study of the deposit at Climax, Colorado. The model of the origin of the Climax deposit, once considered a unique molybdenum occurrence, has been applied widely

TABLE 1 Availability, Demand, and Principal Foreign Sources for 32 Nonfuel Mineral Commodities

Cumulative	New Materials: 1978 ^a			Ratio of Reserves to Cumulative Demand: 1976-2000 ^b		Principal Foreign Sources in 1977 ^c (Percent of Total U.S. Imports)
	Percent Produced Domestically	U.S. Demand in Metric Tons	1978 Value in \$ Million	U.S. Alone	Entire World	
Chromium	0	590,000	600	<0.1	9.5	USSR 41, South Africa 15
Manganese	0	1,300,000	200	0	4.6	Gabon 29, Brazil 18
Cobalt	0	8,600	150	0	1.2	Zaire 62
Tantalum	0	750	86	0	1.2	Malaysia, Thailand, Canada
Columbium	0	2,600	45	0	>10.0	Brazil 57, Canada 14
Tin	0.2	50,000	700	0.1	1.5	Malaysia 50, Bolivia 18
Platinum group	0.2	65	500	0	3	South Africa 74, USSR 8
Antimony	6	16,000	63	0.1	1.8	South Africa 38, Bolivia 16
Nickel	6	170,000	750	<0.1	2.2	Canada 56, New Caledonia 9
Aluminum	8	5,300,000	6,400	<0.1	5.8	Jamaica 28, Australia 23
Asbestos	16	580,000	170	0.2	0.5	Canada 94, South Africa 4
Fluorine	18	550,000	110	0.1	0.4	Mexico 59, South Africa 17
Zinc	31	1,000,000	680	0.6	0.8	Canada 42, Mexico 6
Silver	33	3,500	620	0.4	0.5	Canada 46, Mexico 24
Gold ^d				0.6	1.1	Canada 40, USSR 33
Tungsten	38	8,700	160	0.4	1.4	Canada 25, Bolivia 19
Potash ^e	39	5,900,000	450	0.9	>10.0	Canada 95, Israel 3
Cadmium	39	5,100	27	1.0	1.1	Canada 25, Mexico 15
Selenium	42	500	17	1.9	3.5	Canada 41, Japan 18
Beryllium	43	63	12	3.1	>10.0	Brazil 56, Argentina 21
Mercury	43	2,000	9	0.3	0.9	Algeria 31, Spain 31
Titanium ^f	48	460,000	230	1.4	4.1	Australia 48, Canada 22
Iron	58	87,000,000	19,000 ^g	1.5	5.1	Canada 39, Japan 17
Barite	60	2,500,000	58	1.3	1.3	Peru 28, Ireland 22
Lead	76	700,000	530	1.0	1.1	Canada 27, Mexico 26
Vanadium	76	6,300	43	0.2	7.8	South Africa 54, Chile 26
Copper	77	1,700,000	2,300	1.5	1.6	Canada 24, Chile 24
Sulfur	90	13,000,000	550	0.5	0.9	Canada 59, Mexico 39
Rare earths ^g	90	18,000	—	9.3	8.0	Australia 43, Malaysia 32
Lithium	144	3,900	25	2.8	—	
Phosphate	180	34,000,000	590	3.6	6.5	
Molybdenum	200	30,000	330	2.9	2.1	

^a The emphasis here is on *new* material added to the U.S. economy. Data principally from U.S. Bureau of Mines: Mineral Commodity Summaries, 1979.

^b Data from U.S. Bureau of Mines: Mineral Trends and Forecasts, 1979.

^c Data from U.S. Bureau of Mines: Minerals in the U.S. Economy, 1979. Whenever possible data were traced back to the countries operating the mines, but the iron and selenium from Japan were not traced to their ultimate source.

^d The United States produced 31 metric tons of gold. Imports plus the new U.S. metal equaled exports, and each was 171 tons valued at about \$1100 million.

^e Tonnage as oxide.

^f Includes titanium as metal (3 percent) and nonmetal (97 percent) in 1977.

^g Priced as pig iron; if priced as steel the value would be much higher.

in exploration and has led to the discovery of many new deposits, such as that at Henderson, Colorado (see Wallace, Chapter 2), which is now the world's fourth largest producing deposit of molybdenum.

Other genetic models of mineral deposits have played major roles in the discovery of significant ore deposits. Models of how ore concentrates in various stratigraphic horizons in igneous rocks have led to the discovery of several economic nickel deposits in magnesium-rich lavas in Australia and Canada and to a possibly economic platinum deposit in Montana (see Chapter 4). The recognition of age and tectonic factors has led

to the discovery of potentially economic uranium deposits in South Dakota (see Chapters 6 and 8). Consideration of processes in regional sedimentary basins has led to the successful location of lead–zinc deposits, for example, in paleokarsts in central Tennessee and in a reef complex in Missouri (Chapter 6). Reconstructions of paleoclimates provide criteria for exploration for phosphate deposits (Chapter 8) and for nickel–laterite and bauxite deposits (Chapter 7). Other examples of genetic models either leading directly to, or providing criteria for, discovery of new deposits of various metals are mentioned in the chapters of this report.

ORE-FORMING PROCESSES

Many processes operate on and within the earth to modify the character of rocks. Under the proper circumstances some of these processes concentrate the mineral substances necessary for our economy. Under other circumstances the same processes may dissipate otherwise economic concentrations of materials.

Geologic, geochemical, and geophysical processes that form mineral deposits are extremely variable. Different types of rocks react in different ways with different fluids to yield different types of ores surrounded by different types of alteration in different structural situations. The number of possible combinations of processes and factors is enormous. Moreover, the processes are rarely equal in their degree of development and typically exhibit different aspects when sampled or observed at different points. Thus, an overall knowledge of the various facets of mineralization is necessary. The anatomy and physiology of entire systems need to be understood: the whole basin for sedimentary ores, the whole circulation system from input to discharge for a vein deposit, the entire hydrologic regime for Mississippi Valley–type lead–zinc ores. Details of major ore-forming processes—magmatic, hydrothermal, diagenetic, sedimentary, and weathering—are reviewed in the chapters of this report, and the distribution of mineral commodities with respect to these processes is shown in Table 2.

An ore body may be the product of a number of ore-forming processes, and traditional, discipline-oriented investigation may treat only certain aspects of the entire system. For example, in a geothermal area, the deep circulation, consequent heating, and reactions with wallrock of groundwater might be separately investigated as aspects of deep weathering, hydrothermal alteration, or metamorphism, depending on the interests and expertise of the investigator. Similarly, the processes leading to mineralization on the seafloor might equally be considered as hydrothermal or sedimentary, and the isochemical recrystallization of the product might be diagenesis or metamorphism. The complexity of processes in the formation of any individual deposit points out the need for multidisciplinary research in order to understand the total system.

In developing a research strategy for ore deposits there are two levels of inquiry; problems at each level require rather different approaches (Chapter 9). The first level deals with broad processes involving time and place. As an example, porphyry copper–molybdenum–gold ores appear to be spatially associated with subduction-related magmatism, as in the circum-Pacific belt. Furthermore, in southern Arizona, the porphyry copper deposits are almost exclusively associated with Laramide igneous rocks to the exclusion of comparably abundant mid-Tertiary rocks of otherwise similar characteristics. The reasons for this association are not clear. Although a knowledge of the existence of the association is useful in itself, an understanding of the causal connection may well lead to the identification of previously unsuspected mineralized areas. The second level involves more local features such as the association of ore with certain types of altered rock or with faulting at a specific time, usually applied to an individual deposit. The processes responsible for such an association may be understood in terms of a chemical–

TABLE 2 Geologic Sources of 32 Nonfuel Mineral Commodities

Commodity	Geologic Sources by Broad Genetic Class ^{a,b}					Major Additional Potential Sources
	Magmatic	Hydrothermal	Diagenetic	Sedimentary	Weathering ^c	
Chromium	oooo					Laterites
Manganese		o		ooo	o	Seafloor nodules
Cobalt	o	o	ooo		o	Seafloor nodules
Tantalum	oo			ooo		
Columbium	ooo				oo	
Tin	o	o; ●		ooo	oo	
Platinum	oooo	o; ●		o		
Antimony		oooo; ●				
Nickel	oo				oo; ●	Seafloor nodules
Aluminum					oooo; ●	Al-rich sedimentary and igneous rocks
Asbestos		oooo; ●				
Fluorine		ooo; ●		o; ●		Phosphate by-product
Zinc		o; ●	ooo; ●	o	o	Zn-silicate laterite
Silver	o	ooo; ●●	o; ●			
Gold	o	oo; ●●		ooo; ●		
Tungsten		oo; ●●				Nonmarine brines
Potash				oooo; ●●		
Cadmium		oo; ●	ooo; ●	o	o	
Selenium	o	oooo; ●●				Coal by-product
Beryllium	oooo	o; ●●				Greisens
Mercury		oooo; ●●				
Titanium	oo; ●			ooo; ●		By-product of Cu-Mo
Iron	o	o; ●		ooo; ●●	oo; ●	
Barite		oo; ●		oo; ●●	o; ●	Alkalic igneous complexes
Lead		oo; ●	ooo; ●●●●	o		
Vanadium	ooo		oo; ●			V-rich shales, oil by-product
Copper	o	oo; ●●●●	oo; ●	oo		Seafloor nodules
Sulfur	o	oo; ●	oo; ●●●●			Petroleum, coal, gypsum
Rare earths	oo; ●●●●	o		ooo; ●		Phosphate by-product
Lithium	oo; ●●●		oo; ●●			Li clays, brines
Phosphate	o			ooo; ●●●●	o; ●	
Molybdenum		oooo; ●●●●				

^a Explanation of symbols: o, world production in 1970s; ●, U.S. production in 1970s. In an approximate fashion 1, 2, 3, and 4 symbols denote 0–25, 25–50, 50–75, and 75–100 percent of production, respectively.

^b Assignment to broad genetic geologic classes is easily done in most instances, but some are highly ambiguous.

^c Many ores of all occurrence types are modified by weathering. Only those that concentrate minerals to ore grade from what would have otherwise clearly been waste rock are included here.

physical theory or geologic theory, or the association may simply be a well-established empirical observation without an understanding of the processes. Clearly, the major goals of future research should be to identify regional as well as local factors that determine the presence of ores.

THE PROMISE OF TECHNOLOGY

Our understanding of the genetic processes that are responsible for various types of mineral deposits has progressed at an accelerating rate since World War II. The integration of new technology for field and laboratory studies with the increased competence of the scientists has led to a more quantitative, theoretical approach. We have benefited, for example, from instruments capable of measuring stable and radiogenic isotopes, the properties of fluid inclusions in minerals, and the *in situ* chemical composition of minute samples. The quantitative application of thermodynamics and chem-

Overview and Recommendations

ical kinetics to complex field situations involves difficult computations of mass and energy transfer that were virtually impossible until the advent of modern computers. The remote-sensing capabilities of satellites and new geophysical techniques have not only been an aid in exploration for ores but have permitted an interpretation of the areal and depth distribution of many mineral deposits. The availability of up-to-date scientific equipment has been a basic requirement for achieving an improved understanding of ore deposits and for effective application of that knowledge.

Even more important than the physical advances in equipment is the versatility of today's earth scientists. New concepts of ore-forming processes are evolving from scientists who are able to bring electron microprobes as well as rock hammers, computers as well as phase equilibria, mass spectrometers as well as maps, LANDSAT images as well as microscopes to bear on difficult problems.

The development of our understanding of ore deposits appears to be running a course parallel to, but two or three decades behind, that of global geology. In the half century prior to World War II there was considerable speculation about the permanence of continents and oceans, the distribution of ancient faunas, and the apparent fit of continental masses on opposite sides of the Atlantic Ocean. Extensive studies since 1945 of the morphology of the ocean basins, global seismicity, magnetic patterns in the oceanic crust, and the development and application of radiometric dating methods led to the theory of plate tectonics in the 1960's. This theory dramatically systematized geologic thought regarding the interrelationships among fields such as seismology, paleomagnetism, paleoclimatology, sedimentation, stratigraphy, structural geology, petrology, and fuel and nonfuel economic geology. In the study of ore genesis, we are now in a position quite analogous to that of the development of the model of plate tectonics in the early 1950's. Many tools have been developed, testable concepts are being formulated, and processes that were only subjects of speculation for decades are now being examined quantitatively. As reviewed in the accompanying chapters, some of the major problems are well on their way to solution; other questions remain, and unifying models still need development.

Full cooperation between the academic community, government, and particularly industry will be necessary to maximize the scientific and technical advances. Industry controls access to most of the deposits that might be chosen for such studies and possesses a large and necessary pool of scientific expertise and descriptive information.

The scope of multidisciplinary studies needs to be broader than just the immediate environs of the deposit; it must include the regional geology, geochemistry, geophysics, and hydrology.

Three possible approaches to increased multidisciplinary efforts are the following:

1. *Coordinated projects.* Individual researchers working on specific questions related to the same overall problem could coordinate their efforts to produce integrated multidisciplinary results. This approach could be implemented without creating any new organizational structure. However, there is a need for both individual and fiscal commitment over the term of the project if significant advances in understanding are to be achieved. A current example of such a multidisciplinary project is the study of the Kuroko massive sulfide ores in Japan, which involves the cooperative efforts of about 30 scientists from the United States, Canada, and Japan.

2. *Field stations.*⁴ Facilities located close to important types of mineral deposits could provide a focal point for coordination and continuity of multidisciplinary research. A rotating crew of industrial, academic, and government scientists, supported by a continuing technical staff and basic laboratory facilities, would conduct research on related aspects of the same problem. In addition to providing a central facility from which to conduct research, field stations could provide (a) an effective means of transfer of information during the various stages of investigation and (b) a locale to test new ideas,

tools, and techniques. Because the rotating crew of investigators would consist of industry representatives and scientific personnel from academia (possibly on sabbatical leave) and government, the resulting genetic concepts developed through the field-station approach may have more direct application to exploration.

3. *Institution.* An institution could provide for long-term and broad investigations into difficult problems such as the physical chemistry of ore-forming fluids or the geochemistry of metals in sedimentary environments. It would enable 10–20 scientists of diverse scientific backgrounds, plus a supporting staff, to work as a team toward a scientific goal. Such an institution might be attached to a university, a government agency, or an independent research organization. A model of such an institution might be the Carnegie Institution of Washington's Geophysical Laboratory.

CURRENT FUNDING LEVELS OF BASIC RESEARCH IN MINERAL GENESIS

The nation's investment in basic research directed toward nonfuel mineral resources is small in terms of the contribution that these minerals are currently making to our economy (compare commodity values in Table 1 and research expenditures in Table 3).

Most of the research dealing with nonfuel mineral resources that eventually appears in the scientific literature is funded by the federal government. State geologic surveys and a few privately funded institutions also sponsor or conduct research that may increase

TABLE 3 Expenditures of the USGS and NSF in the Area of (Nonfossil Fuel) Mineral-Resources Research (in Millions of Dollars)^a

Expenditures	FY 1978	Estimated FY 1981
U.S. Geological Survey		
Continental U.S. Mineral Appraisal Program (CUSMAP)	\$4.9	\$4.8
Alaskan Mineral Resource Appraisal Program (AMRAP)	\$4.5	\$4.2
Wilderness lands	\$6.2	\$8.6
Resource information and analyses ^b	\$4.0	\$4.2
Development of assessment techniques ^c	\$9.6	\$9.8
TOTAL USGS mineral-resources research	\$29.2	\$31.6
National Science Foundation		
NSF earth sciences		
Economic geology	\$0.1	\$0.3
Economic geophysics	\$0.3	\$0.05
Economic geochemistry ^d	\$0.5	\$0.9
NSF integrated basic research		
Deep mineral resources (exploration and solution mining)	\$1.2	\$0
TOTAL NSF mineral-resources research	\$2.1	\$1.25
TOTAL USGS and NSF mineral-resources research	\$31.3	\$32.85

^a The information in this table has been provided by J. Hower (NSF and University of Illinois), P. R. Brett (NSF), J. S. Dickey (NSF), P. B. Barton, Jr. (USGS), B. A. Morgan (USGS), and J. J. Hemley (USGS).

^b In 1978, Resource Information and Analyses Program was divided into Commodity Studies (\$1.9 million) and Mineral Information (\$2.1 million).

^c In 1978, Development of Assessment Techniques Program was divided into Exploration/Evaluation Techniques (\$4.3 million) and Resource Processes Program (\$5.3 million).

^d In 1981, the Geochemistry Program was divided into two groups—petrology (\$0.5 million) and geochemistry (\$0.4 million).

our knowledge of mineral deposits. Industrial studies, although often related more specifically to finding and evaluating ore and less likely to lead to scientific publication, have contributed to our understanding of ore deposits. For example, scientific investigations by industry of the deposits at El Salvador (Chile), Bingham (Utah), the Viburnum Trend (Missouri), Climax (Colorado), and Butte (Montana) have led to publications of great scientific merit.

Within the federal government, the U.S. Geological Survey (USGS) and the National Science Foundation (NSF) dominate the funding of the basic scientific research on ore deposits; their efforts are summarized in Table 3.⁵ Other federal agencies, particularly the U.S. Bureau of Mines, the Department of Energy, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the Office of Surface Mining, and the Smithsonian Institution, sponsor research that increases the basic scientific knowledge related to ore deposits.

The minerals industry spends hundreds of millions of dollars annually probing and exploring for the presence of ore bodies; however, little drilling is being done by government or industry in direct support of basic research on mineral deposits. There are several reasons for this:

1. The major reason for limited drilling is the nature of the funding pattern wherein both the NSF and the USGS tend to support many small projects whose annual budgets are of the order of \$0.02 million to \$0.2 million. Even a modest test hole would consume a substantial proportion of the funds available to a single project; thus a drilling strategy is seldom contemplated seriously.
2. There is a widely held opinion that exploration should be done only by industry and that because science-oriented drilling might inadvertently find ore, such drilling should be controlled by industry.
3. Most areas where there is already sufficient justification for scientific drilling are in the vicinity of mines and prospects. Because of the competitive nature of the mining industry, there is a reluctance to guarantee release of what might prove to be valuable proprietary information.
4. About \$500 million/year is already being spent on drilling by federal agencies for specific mission purposes.⁶ The locations of most of the ongoing drilling for mission purposes unfortunately are not in areas that would provide much of the needed information for advance of metallogenic models. Efforts are now being made by the Continental Scientific Drilling Committee of the National Research Council to maximize the potential scientific return on this drilling effort.

TRANSFER OF KNOWLEDGE ON MINERAL RESOURCES

Despite recent encouraging trends in the education of persons who will deal directly with the technical aspects of mineral resources, the benefit to society may be small unless useful information is transferred to those who make decisions on societal questions (see Chapter 10).⁷ Unfortunately, a large gap in understanding and communication persists between the practitioners of the geologic sciences and the makers of policy.⁸ Because policymakers to a large extent reflect the collective will of the electorate, the interaction between the electorate and geoscientists demands attention. Economists, lawyers, journalists, and others who move to positions of policy formulation or public opinion molding must acquire a better understanding and awareness of the concepts of mineral resources and the ability of our planet to provide materials and to absorb wastes from our civilization.

The education of nontechnical students in the appreciation of the interplay of science, technology, economics, law, and public policy related to mineral resources has not been

overwhelmingly successful (see Chapter 10). Continuing education could contribute to an improved appreciation of this interplay and to the needed transfer of information.

NONFUEL MINERAL SUPPLY

In forecasting the availability of mineral resources, considerable attention has been devoted to the adequacy of mineral supply, particularly the ratio of reserves to cumulative demand, as noted in Table 1. Other forecasting efforts have been directed toward estimation of economic or possibly economic resources; present and probable future demands; the probable magnitude of undiscovered resources; the evaluation of real or potential shortfalls; and the use of substitutes, recycling, and conservation to stretch our resources.

Despite these efforts there remains a long-standing controversy between the "catastrophists," who foresee the future exhaustion of mineral resources, and the "cornucopians," who insist that we merely need to modify technology to tap unlimited resources.⁹ The truth probably lies somewhere between these two extreme positions, but attempts to define the availability of minerals have been thwarted by (1) the gross inadequacies of existing geologic data, (2) a lack of adequately tested models or methods to predict the presence and magnitude of mineral deposits, and (3) an inability to forecast pertinent economic and social factors. Although we address only the first two problems here, the third must not be forgotten.

Some resources, such as the number of trees, the acres of arable land, or the quantity of possible hydroelectric power, can readily be measured or estimated. A few resources are effectively "without limit" compared with the present or projected needs of our civilization, e.g., magnesium in the oceans and iron and aluminum in common rocks. The extent of some other mineral resources is known with a fairly high degree of precision, e.g., approximately how much coal is potentially recoverable from a certain area at the present level of mining technology. We could therefore predict the duration of the supply at a given rate of production. Oil reserves are harder to evaluate¹⁰; the wide range of recently published reserve estimates bears testimony to this. It is even more difficult to make anything but rough estimates of the resources of metals such as copper, lead, zinc, silver, gold, manganese, uranium, or titanium.

RESERVES

Studies of mineral availability typically focus on *reserves*, those known deposits from which usable minerals can currently be extracted legally and at a profit. In a broader context, *resources* include reserves, plus the known, but subeconomic, mineral concentrations that might eventually be used, plus the undiscovered deposits, both economic and subeconomic. The relationship between current demand and current reserves varies widely among commodities, as documented in Table 1.

Reserve figures are not an adequate measure of long-term resource availability, because they vary with economic, social, and technological factors (see Chapter 1). In undeveloped properties, and even in producing mines, the actual reserve situation is often obscured by the economics of exploration and development because it may be a poor investment of capital and sometimes an unwise tax strategy to block out reserves that will not be mined for 20 or more years. Thus, reserve figures tend to be rather conservative, and reserves tend to be replenished as demanded by commercial planning. This in part explains why past pessimistic estimates of mineral availability based on reserve figures have consistently been proven wrong. Nevertheless, yesterday's performance does not justify complacency today regarding favorable long-term prospects for resource supply, as the 1970's have so painfully proven for petroleum.

Overview and Recommendations

Metal prices have been suggested as another possible measure of long-term availability. However, an analysis of historical metal-price trends indicates that most real (constant dollar) prices have declined or have remained somewhat constant over long periods of time, despite progressively increasing mineral demands.¹¹ A complete history of mineral prices would probably show a troughlike pattern over time for each commodity; most of the commodities listed in Table 1 are either located in a stable position within the trough or are in a mode of increasing prices. A precise interpretation of metal prices as an indicator of long-term mineral availability is complex and compounded by many factors.¹² Therefore, we suggest that additional measures of long-term availability be considered: exploration costs and grade-tonnage relationships.

EXPLORATION COSTS

Extrapolation of recent trends indicates that exploration expenditures alone (not including costs of development, production, transportation, refining, interest, taxes, and environmental protection) may become a prime economic factor in the development of nonrenewable resources. The trend of exploration costs can be measured by *exploration effectiveness*, which is the ratio of value discovered to value expended in exploration (treated in detail in Chapter 1). Fortunately, exploration effectiveness is still a large number: 55 for Canada from 1966 to 1970, certainly lower for the United States and western Europe, and probably higher for the relatively less-explored regions of the earth.

Deposits that are easily found are becoming scarce. In Canada, exploration effectiveness has decreased by a factor of 3 (from 160 to 55) in just two decades—essentially increasing the exploration costs of a deposit by a factor of 3. Similar information has never been published for the United States, but one estimate of typical exploration cost by Lowell¹³ is that the cost of finding a porphyry copper deposit in the southwest United States increased from \$20 million in 1966 to \$50 million in 1976, an increase that is greater than inflation during the same period. Although precise extrapolation of such trends in exploration cost into future years is highly uncertain, we need not look too far into the next century before the cost of systematic searches for new deposits may dramatically increase the resultant mineral prices.

GRADE

The quantity of metal per unit mass of rock, the *grade*, is highly variable. For example, some veins and massive copper sulfide deposits may contain as much as 10 percent copper; copper-rich shales, such as those mined in Zambia, may contain 4 percent; and a typical large-tonnage porphyry deposit may contain about 0.6 percent copper. In the porphyry deposits, rock is not mined and processed to extract copper if the grade is less than about 0.3 percent; a precise economic cutoff grade depends on price and a variety of costs such as those involved in mining, beneficiating, and environmental protection. If low-grade “waste” must be removed anyway to get at deeper ore, alternative procedures such as dump leaching (solution mining) are used to extract metal from rock that would otherwise be considered as waste. Large amounts of rock containing 0.1–0.3 percent copper are known to exist, and there are enormous volumes of rock containing approximately 0.01 percent copper. The total quantity of copper in “barren” rocks in the upper few kilometers of the continents probably exceeds that in proven reserves by a factor of from 10,000 to 100,000.

The enormous quantity of low-grade materials does not mean that there is an “endless” resource of metallic ores. As the grade approaches lower values the *mineralogical limit*¹⁴ (see Chapter 1) is reached, at which point the extraction costs increase dramatically. The mineralogical limit is the concentration below which an element no longer forms

a distinct mineral phase that can be physically beneficiated or chemically leached to provide a concentrate amenable to refining. The grade at which the mineralogical limit is reached varies widely from one metal to the next and is strongly dependent on the physical and chemical factors operative when the rock formed. Below the mineralogical limit, the metallic element is present solely as randomly distributed atoms in the major minerals of the earth's crust. To extract a metal present in "ore" at a level below the mineralogical limit would require smelting or otherwise processing the bulk rock, thereby increasing perhaps a hundredfold the energy and physical plant requirements. For most metals the resultant costs and energy expenditures make extraction below the mineralogical limit impractical.

Regardless of the mineralogical limit, the cost of production is not measured simply in dollars but also in terms of the consumption of other resources. So long as inexpensive energy could provide leverage, one could imagine effective utilization of larger and larger quantities of ever-decreasing metal concentrations in rocks. But we have now come to a set of boundary conditions that were not perceived as restraints a generation ago. The prospector/miner/processor no longer works in an isolated world; today other interests demand, and frequently receive, higher priorities for land, water, energy, manpower, and other resources. Clearly, it is to society's advantage to find, identify, and use the most economically and environmentally acceptable resources.

GRADE-TONNAGE

One of the requirements for successful long-range planning is a knowledge of the resource endowment of large regions of the earth's crust. Grade-tonnage relationships may be of considerable use in making such estimates; they must be based on thousands of analyses of rocks and ores, and they are suspected of showing two general types of elemental distributions: monomodal and bimodal.

A monomodal distribution, as shown in Figure 1, is the common pattern for the abundant crustal elements, such as aluminum, magnesium, and iron. The peak on the abundance curve of a given element generally represents the modal crustal abundance for the given element. Ore-grade materials are generally located at the high-grade edge of such a distribution. From the monomodal distribution one could deduce that, by increasing the market value of the ore or by technological improvements leading to lower costs (either would allow the use of continually lower grades), there would be an increasing amount of mineral resources that could be tapped.

Skinner¹⁵ has proposed that many metals do not have a monomodal distribution but in fact have a bimodal (see Figure 1) or even multimodal distribution. There may be geologic processes that concentrate a small fraction of the total metal into ore deposits and thereby modify the high-grade edge of the simple monomodal curve by creating an additional mode. The actual shape and position of the grade-tonnage curve for each commodity is critically important to our long-range resource outlook; if ores do occur in separate modes, then simply lowering ore grade a small amount will not provide vast quantities of metals without disproportionately raising the costs.

Some of the factors that lead to the variability in the composition of rocks and to the formation of ore-grade materials at the high-grade edge of grade-tonnage curves are described by Holland and Petersen in Chapter 3. Their analysis of the distribution of uranium concentrations through a variety of uranium-enriched rock types suggests that the curve of uranium concentration versus tonnage is complex but probably monomodal and that large tonnages of currently subeconomic but potentially recoverable uranium resources do exist.¹⁶ There are too few data to extrapolate this conclusion to other commodities, but we must pursue the characterization of geochemical distributions, because the understanding of the grade-tonnage relationship for each commodity is fundamental to proper resource assessment.

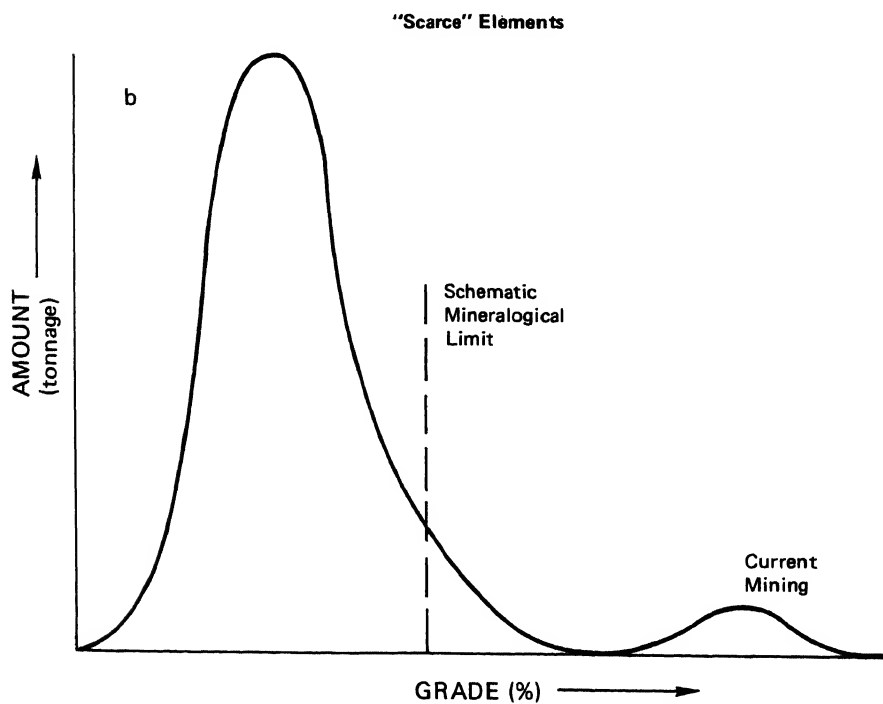
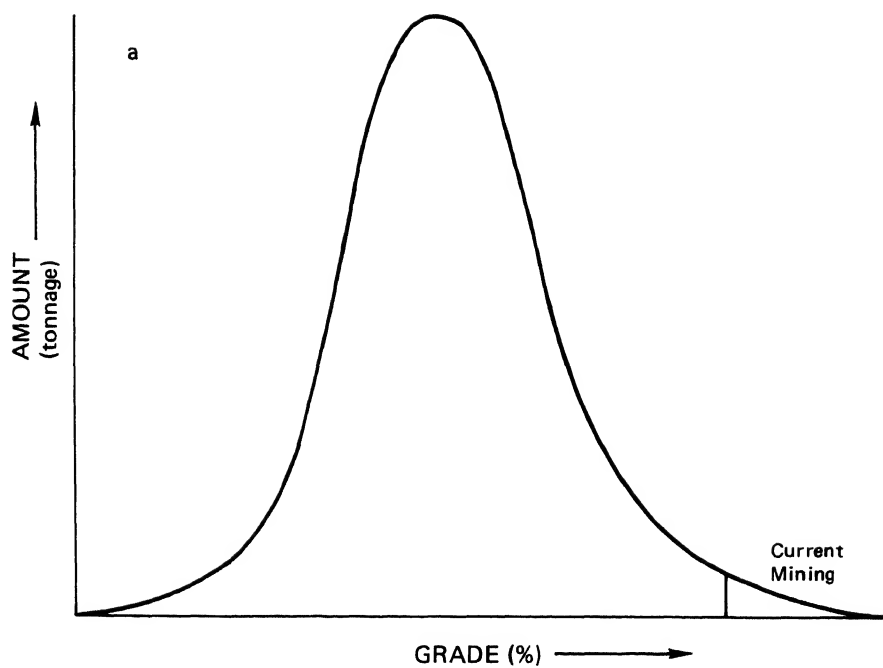


FIGURE 1 a, A monomodal geochemical distribution schematic of the patterns for the "abundant" crustal elements, such as iron and aluminum. b, Bimodal geochemical distribution for the "scarce" elements, such as tin, tungsten, and lead. Current mining appears to be limited to the higher-grade portion of the curve. A mineralogical limit (see text) is sketched on the diagram. Not all "scarce" metals are necessarily bimodal or multimodal; Holland and Petersen (Chapter 3) propose that uranium may have a monomodal distribution.

LAND MANAGEMENT

Although the federal government owns over 760 million acres of land (about 33 percent of the United States), "the United States still knows little about the total mineral resource potential of its [federal] land."¹⁷ Nevertheless, decisions on use of this land are being made in response to concerns related to national defense, environmental degradation, wilderness and wildlife preservation, the desire for recreational facilities, expanding urbanization, and increasing shortages of energy and other resources. Decisions on closing large tracts of federal land to mineral exploration and mining have been made prior to a thorough assessment of their resource potential.² An improved understanding of mineral resources would enable us to make more efficient and comprehensive assessment of land values. However, because each new exploration concept for mineral deposits offers potential for land that was previously examined, mineral assessments can never be considered complete.

CONCLUSIONS AND RECOMMENDATIONS

1. The opportunities for rapid advancement of our knowledge of mineral genesis and the application of that knowledge to evaluate more fully and to improve our resource potential now coincides with a national concern for the availability of strategic and critical minerals. Therefore:

The study of mineral deposits in the field and laboratory should be intensified and vigorously pursued jointly by government, industry, and academia with emphasis on the acquisition of a genetic understanding of mineralization to increase significantly the efficiency of exploration and the accuracy of resource assessment.

The improvements of our genetic concepts and their applications to exploration will require a substantial period of time. Genetic concepts and their applications provide the exploration guidance needed to satisfy the mineral demands for the future. Thus the intensified effort should begin immediately. This should represent new effort, not merely reprogramming other activities, because many basic studies provide information that is essential to a mineral-resource program.¹⁸

2. The present format of geologic study of mineral deposits usually consists of small projects, which limit the opportunity to achieve the multidisciplinary blend necessary to investigate the complex processes that concentrate minerals. Therefore:

A significant portion of future research on mineral deposits should consist of large, multidisciplinary, coordinated studies.

Large projects will require institutional coordination among industry, academia, and government as well as interdisciplinary collaboration. The studies should involve mutually supporting field and laboratory investigations and may require additional technical support such as drilling for scientific purposes. Three possible mechanisms for initiating such projects are (1) through coordinated projects involving commitment of a number of scientists and of resources for the term of the project; (2) through establishment of field stations near important types of deposits to serve as focal points of research; and (3) through establishment of an institution, public or private, to provide a base for broad multidisciplinary investigations of ore-forming processes.

3. Accurate assessments of the long-term availability of mineral resources are dependent on several types of information. Two important types that are needed for

national mineral policy formulation are not readily available: grade-tonnage relationships and trends of exploration effectiveness. Calculation of grade-tonnage relationships indicative of the overall resource endowment of the earth's crust, requires the synthesis of several thousands of rock analyses from mines, prospects, and "barren" rock bodies. Estimation of trends in exploration effectiveness, a measure of increasing scarcity of easily found deposits, requires cost information from private industries. However, there are no established mechanisms to collect and distribute this information. Therefore:

Professional societies representing both the concerned scientists and industry should identify a means to collect, protect, and disseminate (1) grade-tonnage data and (2) information on exploration effectiveness.

We recognize the existence of, and reasons for, proprietary interests in mineral information. Nevertheless, individuals and companies should be encouraged to make such information (collected at great expense and thousands of man-years of effort) available without compromising the legitimate proprietary interests of industry and stockholders.

4. Scientific findings and their implications to mineral resources need to be communicated to policymakers, to public-opinion molders, and to the general public. An improved mineral-resource knowledge base should form a foundation from which decisions are made regarding difficult trade-offs such as those involving land-use, economic, and foreign policies. Therefore:

Educational institutions should (1) establish courses that give balanced and integrated attention to the scientific, technical, economic, environmental, social, political, and legal aspects of natural resources and their uses and (2) provide continuing education in natural resources.

NOTES AND REFERENCES

1. Mineral supplies and forecasts are drawn from the following publications of the U.S. Bureau of Mines: *Mineral Commodity Summaries*, 1979; *Minerals in the U.S. Economy*, 1979; and *Mineral Trends and Forecasts*, 1979. (All are available from the U.S. Government Printing Office, Washington, D.C.).
2. See General Accounting Office Report EMD-78-83 (1978): *Interior's Programs for Assessing Mineral Resources on Federal Lands Need Improvements and Acceleration*, 32 pp. (U.S. Government Printing Office, Washington, D.C.).
3. "Ore" is material that can legally be mined and processed at a profit. Without the ability for economic recovery, even a rock containing thousands of dollars per ton worth of gold may not constitute "ore" if it cannot be mined, for example, if it occurs in a national park. The term "mineral deposits" refers to all mineral concentrations regardless of their legal or economic extractability.
4. A recommendation of the workshop on *Research Frontiers in Exploration for Non-renewable Resources*. A. W. Rose, H. L. Barnes, C. W. Burnham, and H. Ohmoto, eds., The Pennsylvania State University, University Park, Pa., NSF/RA-770031, 164 pp., 1977.
5. Table 3 indicates that the USGS budgeted \$31.6 million in 1981, although only about 20 percent was allocated for programs on fundamental processes involved in ore formation. The remainder of the budget was for investigating the general geologic framework of ore deposits and the evaluation of the mineral potential of public lands; there has been little emphasis in these programs on the fundamental forming processes. Our incomplete understanding of these processes and our fragmentary knowledge of geologic history set severe limits on our ability to estimate the mineral potential of imperfectly explored ground. The NSF funds about \$1 million annually on process-oriented research in the area of ore formation. In addition, other basic research funded by NSF in the areas of geochemistry, geophysics, and geology has implications on the origin of natural resources (about \$4 million to \$5 million annually) but has not been counted in Table 3.
6. NRC U.S. Geodynamics Committee (1979). *Continental Scientific Drilling Program*, National Academy of Sciences, Washington, D.C., 197 pp.

7. Current university enrollments in the scientific and technical fields related to mineral resources have been increasing, however it is projected that the number of graduates will fall short of industry's needs by 1987. J. H. Johnson, Jr. (1978). Engineering manpower needs of the mining industry, *Min. Congr. J.* 64(3), 39-42, 53.
8. T. F. Bates (1979). Transferring Earth Science Information to Decision-makers, *U.S. Geol. Surv. Circ.* 831, 30 pp.
9. NRC Committee on Mineral Resources and the Environment (1975). *Mineral Resources and the Environment*, National Academy of Sciences, Washington, D.C., 348 pp.
10. L. J. Drew, D. H. Root, and E. D. Attanasi (1977). Importance of physical parameters in petroleum supply models, in *Minerals Policy in Transition*, J. H. DeYoung, Jr., ed., Am. Inst. Min. Metall. Pet. Eng., Washington, D.C., pp. 52-69.
11. U. Petersen and R. S. Maxwell (1979). Historical mineral production and price trends, *Min. Eng. (NY)*, January 26, 25-34.
12. V. K. Smith, ed. (1979). *Scarcity and Growth Reconsidered*, Resources for the Future, The Johns Hopkins Press, Baltimore, Md., 298 pp.
13. J. D. Lowell (1976). Strategy of mineral exploration, in *Research Frontiers in Exploration for Non-renewable Resources*, A. W. Rose, H. L. Barnes, C. W. Burnham, and H. Ohmoto, eds., NSF/RA-770031, The Pennsylvania State University, University Park, Pa., pp. 51-68.
14. B. J. Skinner (1979). Earth resources, *Proc. Natl. Acad. Sci. USA* 76, 4212-4217.
15. B. J. Skinner (1976). A second iron age ahead? *Am. Sci.* 64, 258-269.
16. Data for uranium are the exception. The Department of Energy's (DOE) resource assessment and supply analysis programs receive cost data voluntarily submitted by private industry to provide a basis for estimating costs required for discovery and recovery of uranium resources at levels up to two and a half times the current market price. A reasonably comprehensive geochemical distribution data base for uranium is being developed through DOE's National Uranium Resource Evaluation (NURE) program. This geochemical distribution data base has cost approximately \$75 million and is essentially only for uranium. Cost figures for the hydrogeochemical and aerial radiometric reconnaissance surveys of DOE's NURE program were provided by D. L. Everhart of DOE's Grand Junction (Colorado) office.
17. *U.S. Mineral Vulnerability: National Policy Implications*, Subcommittee on Mines and Mining, Committee on Interior and Insular Affairs, U.S. House of Representatives, 96th Congress, Committee Print No. 9, 1980, 83 pp.
18. Examples of basic studies on the nature and evolution of geologic processes that have become key elements in the mineral-resource research and exploration program are numerous. They include, for example, the studies on the Red Sea brines, the research on the recently discovered hydrothermal "pipes" at 21° N of the East Pacific Rise, and space imagery and remote sensing.

I

RESOURCES AND EXPLORATION

Today's Resource Status— Tomorrow's Resource Problems: The Need for Research on Mineral Deposits

1

PAUL A. BAILLY
Occidental Minerals Corporation

As for the future, your task is not to foresee, but to enable.

ANTOINE DE SAINT-EXUPERY

Only the resource of man can bring the resources of the earth to life.

PENNZOIL COMPANY 1977 ANNUAL REPORT

INTRODUCTION

Less than 100 years ago, Indians of the Northern Plains died of starvation in cold tepees, while camping near outcrops of coal seams and uranium-bearing sandstone, on prairies that today support wheat fields. Do we need a better illustration that (1) natural occurrences that become mineral resources are man-perceived, man-made, and definable only in human terms and (2) civilization depends on agriculture and lithoculture, the latter being a term proposed by Kelly (1974) to describe all the activities involved in the extraction of useful products from the rock formations of the earth?

Given man's sustained curiosity and ingenuity, it is reasonable to assume that we shall tomorrow find new ways to satisfy old and/or new needs; such new ways, unrecognized today, will become evident with time. This optimistic view of the future cannot, however, be a justification for complacency. It behooves us to prepare for the future on the basis of our needs and our resources as we perceive them today, while being on the lookout for new perceptions, new opportunities, and new alternatives.

Man needs minerals for

- Life support: soil, water, salt, and fertilizer;
- Energy generation: coal, oil, gas, and nuclear minerals; and
- Materials for construction of shelters, industrial plants and machines, and for manufacturing appliances and commercial/industrial products.

For the purposes of this report, we shall be concerned only with those more than 60 minerals that occur in solid form as discrete bodies—mineral deposits—but not as common natural rock formations.

A mineral deposit is physically exhaustible and thus irreplaceable. The minerals extracted from it are nonrenewable, but some of them, especially the "materials" minerals, are also increasingly reusable. Also, other commodities may be substituted for most of the "materials" minerals to satisfy the same human needs. The old perception of minerals as completely depletable is slowly being modified (Dunn, 1978), as we realize that throughout history nonrenewable mineral reserves and recyclable stocks have constantly been expanded more readily

than renewable resources (e.g., in the short term it would be easier to double iron production than wheat production) and, further, that any expanded use of renewable resources depends on materials derived from nonrenewable resources.

In discussing mineral resources, we shall use the classification shown in Figure 1.1, despite reservations we have about the use of the word "resources."

This report is concerned with the need for improvements through research in (1) our understanding of the formation of mineral deposits and (2) discovery-oriented exploration for new deposits, i.e., the creation of additional reserves.

ACCESSIBLE AND AVAILABLE SOURCES: RESERVES

In a free market economy a mineral deposit from which usable minerals or commodities can be economically and legally extracted at the time of determination is known as a "reserve." It fits the popular concept of a resource, i.e., a thing to which we can turn when in need, and it also fits the economist's concept of a resource, i.e., it can actually or potentially create new wealth and its value is reflected in a market. However, "reserve" does not cover all mineral concentrations of interest, and earth scientists find the broader definition of "resource" (see Figure 1.1) to be useful.

The controlling factors, sometimes known as the "Five E's," that determine whether a mineral deposit is a reserve are (1) existence of the deposit; (2) extractability of the mineral values; (3) energy and material requirements for extraction; (4) environmental acceptability requirements; and, finally, (5) economics of a possible operation, including capital availability and cost, operating costs, market demand, and societal, fiscal, and legal constraints.

When a feasibility study and a deposit evaluation are prepared, experience shows that at least 50 variable factors are taken into consideration in deciding whether all or part of the deposit can be considered a reserve (Banfield, 1972). Because of these many variables, the amount of reserves is constantly changing. A simple example is the supply of U.S. copper from domestic mines and deposits, as described by Bennett *et al.* in 1973 (see Figure 1.2). In 1973, at a copper price of 75¢ per

pound, U.S. recoverable resources amounted to 118 million tons when a 12 percent rate of return was considered the minimum acceptable profitability, whereas the break-even recoverable resource (no profit) totaled 139 million tons. At that time, a 20 percent decrease in price (to 60) would have lowered the recoverable copper resources to 93 million tons (a 22 percent decrease) and the break-even resources to 118 million tons (a 15 percent decrease). Taking a very conservative position, the U.S. Bureau of Mines, in its January 1974 Commodity Data Summaries, showed copper "reserves" of 83 million tons (see Table 1.1), i.e., the recoverable resources at 50¢ copper and 12 percent rate of return. The price used was above the average for the year 1973 but much below the 1974 average price.

The above copper study is undoubtedly one of the best documented and most reliable evaluations of domestic reserves prepared at any time, in any country. Such carefully prepared reserve estimates have, at best, a 20 percent margin of error at a high confidence level. Hence, one must look at all published reserves numbers with a grain of salt. The U.S. government itself has estimated that roughly four fifths of the U.S. data on reserves are of poor quality (Bosson and Varon, 1977, pp. 216-217). Because of this, in the United States at least, reserves are usually understated.

Practically all metal-reserve estimates made in the past have turned out to be conservative. For example, a 1929 study stated that we had but 10 years' supply of tin left; in 1969, such supply was stated as 15 years (Beckerman, 1977). Also, total U.S. reserves of uranium oxide were estimated in 1950 at 3000 tons. In the next 10 years, 79,000 tons of uranium oxide were produced. In 1960 alone, uranium production amounted to six times the 1950 reserves, but rather than being exhausted by this production, reserves were by then estimated to total 187,000 tons (\$8/lb of uranium), or 62 times the 1950 figure. This example illustrates well a statement by *The Wall Street Journal* (1977) editorialist that "against their own better judgments, geologists do make such predictions; their track record is ludicrous." There is little doubt that the conservative tendency of geologists to understate reserves will continue.

The distinction between "ore reserves" (known materials of economically and legally feasible activity), "identified resources" (ore reserves plus known materials that are at present inaccessible for economic and/or legal reasons), and "undiscovered resources" has not generally been made until the past decade (see Figure 1.1). Moreover, it was rarely emphasized that (1) deposits are continually moving from the "undiscovered" category to the "identified" category and (2) deposits, or parts of deposits, are continually moving in *either* direction between the economically feasible and the subeconomic categories—in response to economic, technological, legal, environmental, and social factors (Bailey, 1976b). Older estimates summed the economic reserves known then, but they were misinterpreted as representing the total mineral endowment of resources in all categories. Thus, there is little wonder that the estimates of "reserves" made in years gone by appear ridiculous today. The science/art of making estimates of the total endowment has been catalyzed by the efforts of M. K. Hubbert and others with regard to petroleum, but efforts in this direction for a wide variety of mineral commodities have only recently been begun (Brobst *et al.*, 1973).

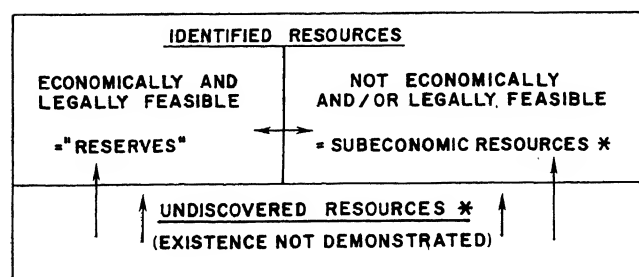


FIGURE 1.1 Classification of mineral resources (after Brobst *et al.*, 1973; Robertson, 1977).

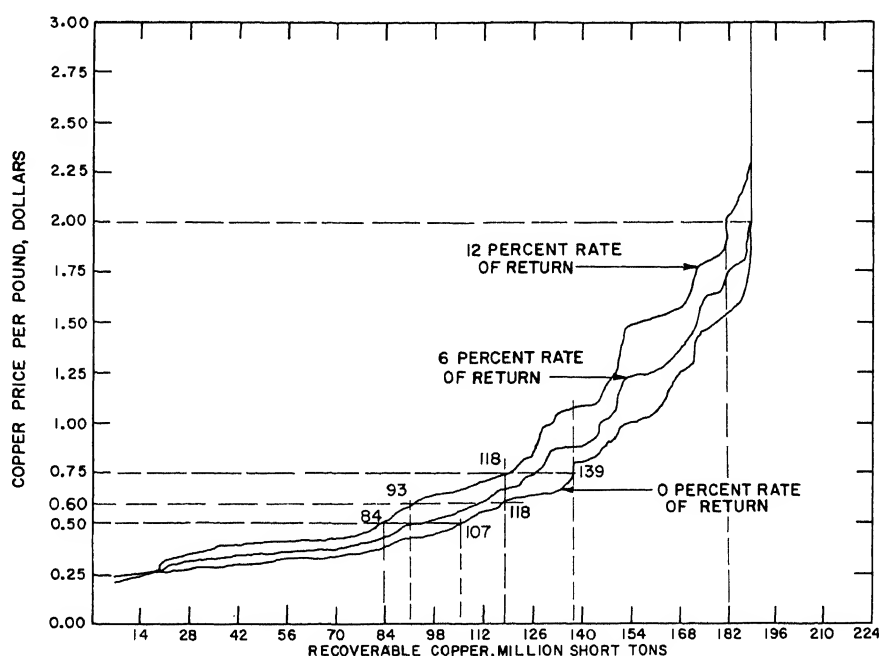


FIGURE 1.2 Total domestic recoverable copper resources, determined in function of copper price and expected rate of return on investment (after Bennett *et al.*, 1973).

In the minds of some geologists the pendulum has swung from impending exhaustion to the other extreme, wherein the truly huge amounts of almost any commodity are available from ordinary rock by virtue of the trace quantities therein, which become large because of the huge amounts of ordinary rock. The latter opinion has captured the minds of some economists, who insist that there will never be a minerals exhaustion because increasing price will increase the size of the "reserve" box, thereby increasing supply. However, this is a fallacy for two primary reasons: (1) Costs are measured not simply in dollars but also in terms of energy, manpower, other natural resources, environmental degradation, and so on. Simply mining granite for the few parts per million of lead, uranium, or silver that it contains would create fantastic demands for energy and water and would create thermal and waste pollution on an unprecedented scale. (2) Once the mineralogical threshold is reached, there is an immediate and immense increase in the cost and difficulty of extracting the metal—so great that the rock is no longer a practical source.

In considering the mineralogical threshold (e.g., lead), metals are present in two physically different forms. The first is as lead minerals (principally galena, PbS , but also as less-common anglesite, PbSO_4 , and cerussite, PbCO_3 , and a few others minerals). Even though they may be present in the ore only to a few percent, such minerals are amenable to physical concentration that results in a high-grade (60–80 percent Pb) concentrate that is conveniently shipped and smelted. If chemical leaching is performed, these minerals may be selectively and completely released without necessarily decomposing the entire rock. Such materials constitute most of the ores now used by man. On the other hand, lead is also present in solid solution in rock-forming minerals, principally feldspar and mica, which

may constitute all of the rock. The concentration of such lead is low, only a few parts per million, but because there is so much rock, the total amount of lead therein is tremendous. To extract the lead by either smelting or chemical leaching requires the total decomposition of all of the rock, which is much more costly in energy than merely grinding the rock and separating out the galena; moreover, because of the low grade, much more (a thousand times more in the case of lead) material must be mined, shipped, treated for extraction, and the waste disposed of in an environmentally acceptable manner. Even allowing for the recovery of a wide range of metals from the same rock, bulk mining of ordinary rock appears totally impractical without huge amounts of cheap energy. Even with cheap energy, the problems of thermal pollution and waste disposal might be overwhelming.

The concept that resources are properly measured in economic, not physical, terms is an economist's viewpoint that appears to be valid over the short term and most applicable to "reserves" estimates (Georgescu-Roegen, 1975; Bailly, 1976a). In this light, we can be confident of an adequate supply of practically all mineral commodities to the year 2000. However, the price-mechanism concept does not reflect the physical limitations of the earth's crust; the requirements for gangue (waste) disposal; the unpredictability of time of discovery; the availability of capital, equipment, and manpower; the time, political, and social constraints on development and production, including access to the deposit; and the related possible scarcities in the future. As Flawn (1965) has stated, there is an ultimate limit to resources that is reached when the total investment of materials and energy required to procure a commodity exceeds its value to society. Thus, it was determined by the Committee on Mineral Resources and the Environment (COMRATE, 1975)

that, under current energy and cost conditions and with our current knowledge of the abundance distribution and mineralogy of copper in the crust, it appeared unlikely that copper ore below 0.1 percent in grade would ever be minable. This obviously tells us that economic terms alone are not adequate to define resources, especially for the "undiscovered resources" that may or may not exist and whose economic value cannot be determined.

ESTIMATION OF UNDISCOVERED RESOURCES

Paucity of reserves has, traditionally, been used to indicate the need for additional research on extraction technology and/or additional exploration for new deposits. The necessity to improve planning for the future, however, and to avoid scarcities, has caused many to try to estimate both the likelihood of extraction-technology breakthroughs and the amount of commodities that may exist in the ground, for discovery and eventual transformation into reserves or subeconomic resources.

This desire has been expressed in estimates by geostatisticians and geologists of the quantities of minerals that may be found in yet undiscovered deposits: the "undiscovered resources" (Figure 1.1). It is unfortunate, indeed, that the word "resource" is now applied to things whose very existence is surmised only by extrapolation, in contradiction of the popular concept of a resource: a thing that can be counted on when in need. However, the English-speaking world seems to be firmly encumbered with this deceptive terminology, which results in the use of numbers for "undiscovered resources" by politicians and journalists with the same degree of reverence and confidence as the numbers used for reserves; in fact, such numbers can be extremely misleading, as they involve immense uncertainties, and they do not describe quantities that can be counted on.

Perhaps as suggested by B. J. Skinner (Yale University, personal communication, 1979), "undiscovered resources" should be labeled "postulated deposits," "reserves" should be retained with its accepted meaning, and the word "resources" should not be used at all to include "postulated deposits."

Nevertheless, for policy formulation and for exploration planning, governments and the mining industry, respectively, are interested in developing estimates of undiscovered resources. Geostatistical and geologic approaches have been used. Many geostatistical techniques have been applied, but most do not arrive at results usable in exploration because they develop only global or regional numbers for total undiscovered resources without indicating which piece of land is more likely to contain a mineral deposit (Folinsbee *et al.*, 1977). These geostatistical approaches have been described and evaluated by Harris (1977), in a thorough, up-to-date publication. The geologic approach in its varied forms follows steps that are similar to those used in exploration planning. Thus, the geostatistical approach has some value for national or global planning and formulation of mineral policies, whereas the discovery-oriented geologic approach, as used by the U.S. Geological Survey and the Geological Survey of Canada, has immediate

application in exploration. The former tries only to foresee the future, the latter tries to enable it. No approach, however, can ever yield results superior to the postulates used to formulate the predictive model.

CURRENT STATUS OF U.S. MINERAL RESOURCES

The estimated apparent U.S. consumption in 1977, the percentage imported in 1977, the domestic reserves in 1974 and in 1978, the identified resources (including reserves and subeconomic), and the hypothetical undiscovered resources (estimated through the geologic approach) for 21 essential mineral commodities are tabulated in Table 1.1. The reliability of such a table to predict the future depends, to a great extent, on political judgment as to the secure availability of imports, on engineering judgment as to the likelihood of technological improvements, on economic judgment as to the growth of the economy, and on exploration judgment as to the likelihood of finding these yet undiscovered resources.

Even a cursory examination of Table 1.1 shows that imported minerals constitute a large segment of our current supplies, especially for manganese, aluminum, chromium, tin, asbestos, fluor spar, nickel, mercury, gold, and platinum. Some potential exists for domestic production of a few of these, but for others, especially the first four, the outlook for national self-sufficiency is poor.

MINERAL EXPLORATION

Exploration, the search for yet undiscovered deposits, is justified for some commodities by (1) the need for new reserves when known reserves are inadequate for the foreseeable future, e.g., exploration for uranium reserves producible at less than \$20/lb of U_3O_8 , and (2) the desire to find deposits that will, it is hoped, be more profitable (i.e., lower cost and/or higher grade) than those currently mined or held as reserves. The latter reason follows the biologic-economic laws of least effort and maximum efficiency; it is applicable to many commodities (e.g., Fe or Al) for which the reserves are very adequate, but for which geological predictions point to the possibility of finding more profitable deposits that can be operated at costs lower than the average production cost for known deposits of the same commodity.

Thus, in the early part of the twentieth century, production from the southwestern United States and the South American Cu deposits replaced that from the Michigan deposits that, today, continue to contain sizable reserves, but of low profitability. The central African Cu deposits were opened in the 1930's, because they promised, and then delivered, higher profits than the southwestern U.S. deposits. Today, Cu exploration continues in Arizona, in spite of large domestic reserves, because some deposits have been discovered recently that are of much higher grade, and potentially more profitable, than those currently mined. The New Lead Belt in Missouri was

TABLE 1.1 U.S. Consumption, Net Imports, Reserves, and Resources of Selected Mineral Commodities

1977 Apparent Consumption ^a	Net Imports as Percentage of Apparent Consumption ^b	Mineral Commodities	Mineral Resources ^{d,g}			
			Reserves as of 1974 ^c	Reserves as of 1978 ^a	Identified Resources Including Reserves	Hypothetical Undiscovered Resources ^f
1.3	98	Manganese, Mn. S.T.	—	—	Large	KDI
2.3	92	Platinum, GM, Mn. Tr. Oz.	3	1	Moderate	Large
5.4	90	Bauxite/Alumina as Mn. S.T. Al.	40	40	Very large	KDI
0.6	89	Chromium, Mn. S.T.	—	—	Insignificant	Insignificant
66.0	85	Tin, thousand M.T. metal	5	40	Insignificant	Insignificant
0.7	83	Asbestos, Mn. S.T.	10	4	Small	Insignificant
1.5	79	Fluorspar, Mn. S.T.	25	16 ^h	Small	Small
230.0	71	Nickel, thousand S.T.	200	200	Large	KDI
5.4	70	Gold, million Tr. Oz.	82	110	Large	KDI
66.0	65	Mercury, thousand flasks	380	407	Small	KDI
15.5	59	Tungsten, Mn. Lb. metal	87.5	275	Moderate	Moderate
1.3	59	Zinc, Mn. S.T.	30	30	Very large	Very large
165.0	47	Silver, Mn. Tr. Oz.	1,300	1,510	Moderate	Large
2.5	38	Barite, Mn. S.T.	75	65	Very large	Very large
120.0	35	Iron ore, Mn. L.T.	9,000	17,000	Very large	Huge
2.2	15	Copper, Mn. S.T.	83	93	Large	Large
1.5	15	Lead, Mn. S.T.	56	28 ^h	Large	Moderate
13.0	0	Uranium, thousand S.T. U ₃ O ₈	337 ⁱ	680 ⁱ	Large	Large
57.5	0 ^j	Molybdenum, Mn. Lb. Mo.	6,300	7,600	Huge	Huge
36.0	0 ^j	Phosphate rock, Mn. S.T.	2,016	3,800	Very large	Huge
11.6	0 ^j	Sulfur, Mn. L.T.	75	205	Huge	Huge

Note: Mn., millions; S.T., short tons; L.T., long tons; M.T., metric tons.

^a Source: Mineral Commodity Summaries, 1978, Bureau of Mines, U.S. Department of the Interior.

^b Source: Status of Mineral Industries, 1977, Bureau of Mines, U.S. Department of the Interior.

^c Source: Commodity Data Summaries, 1974, Bureau of Mines, U.S. Department of the Interior.

^d Source: Mineral Resources, 1975, USGS Professional Paper 820 and "The Politics of Scarcity," by Ph. Connelly and R. Perlman, 1975.

^e Identified resources are defined as including reserves, and materials other than reserves, that are essentially well known as to location, extent, and grade and that may be exploitable in the future under more favorable economic conditions or with improvements in technology.

^f Hypothetical resources are undiscovered, but geologically predictable, deposits of materials similar to identified resources. ("Hypothetical" class of USGS)

^g Resource appraisal terms:

Huge: Domestic resources (of the category shown) are greater than 10 times the minimum anticipated cumulative demand (MACD) between the years 1971 and 2000.

Very large: Domestic resources are 2–10 times the MACD.

Large: Domestic resources are approximately 75 percent to twice the MACD.

Moderate: Domestic resources are approximately 35 percent to 75 percent of the MACD.

Small: Domestic resources are approximately 10 percent to 35 percent of the MACD.

Insignificant: Domestic resources are less than 10 percent of the MACD.

KDI: (Known Data Insufficient)—Resources not estimated because of insufficient geologic knowledge of surface or subsurface area.

^h These considerably reduced reserves result from recent revisions by the Bureau of the Mines; prior reserves numbers based on USGS estimates included inferred reserves.

ⁱ \$10/lb U₃O₈ in 1974 and \$30/lb U₃O₈ in 1978.

^j United States is exporter.

discovered in the 1950's; it contains deposits much higher in grade than those remaining in the Old Lead Belt mines, now closed. Similarly, the central Tennessee Zn discoveries were made in the late 1960's and early 1970's, when Zn reserves were considered adequate; these new deposits are higher in grade than those in eastern Tennessee.

Thus, exploration continues and results in additions to identified subeconomic resources and in the creation of new re-

serves—which places the successful discovery in a favorable competitive position. In a free-enterprise economic system, this makes for the strength and success of the mining industry, which markets products on the basis of international prices.

How costly and how effective is exploration? Even though exploration costs are increasing rapidly, I estimate them to be only 3 percent of the revenue of the nonfuels mining industry. Nonfuels primary mining production, itself, amounts to only 1

percent of the gross national product (Callot, 1970, 1971, 1974). Thus, exploration is only a small cost for a nation; there is no doubt that exploration can continue to be financed from earnings, except during periods of low mineral prices and low profitability. Thus far, exploration has been adequate to maintain reserves at an acceptable level.

Unfortunately, there are no reliable comprehensive cost data on U.S. exploration. Canada is the only country that makes the effort of assembling such data. In 1973, Cranstone and Martin (1973) made an appraisal of Canadian metals exploration results. By adding to their data my own information about the exploration cost of successful projects, I have tried to evaluate the rate of success in metallic mineral exploration according to three parameters [see Tables 1.2 and 1.3 and Figures 1.3(a) and 1.3(b)].

The first parameter is "Exploration Effectiveness," obtained by taking the value of all discoveries, expressed as the estimated gross value of economically recoverable metals, and dividing it by the expenditure for all exploration projects. This gives a measure of the overall effectiveness of the exploration dollar; it quantifies the multiplier effect of each exploration dollar. Such effectiveness can be measured for individual countries or regions, for the mining industry or for individual companies, or for specific commodities. In any case, it is always the integrated sum of exploration effectiveness of many exploration projects.

The next parameter is labeled "Project Effectiveness," for which the gross value per deposit is divided by the exploration cost for that specific deposit. The majority of exploration projects produce no ore and thus have a zero effectiveness. A few projects have a very high effectiveness, a high multiplier, expressed in thousands.

Finally, we can define a third parameter, which I have labeled "Success Ratio"; it is the percentage of the total exploration expenditures that is devoted to successful projects.

Fitting those three parameters together, we see that the overall Exploration Effectiveness is equal to Project Effectiveness multiplied by Success Ratio [Figure 1.3(a)]. How have

these parameters evolved for metal exploration in Canada? Table 1.2 shows exploration expenditures and results, expressed in constant dollars and constant metal prices, for successive 5-year intervals during the period 1951–1970. The annual average of all exploration expenditures for metals in Canada increased during that period from \$24 million to \$98 million. The annual average number of economic metallic discoveries, in Canada, decreased from 14 to 7 per year. The average value of all metal discovered annually remained nearly constant, at \$5 billion.

The overall exploration effectiveness has decreased from 160 during the first 5-year period, to 55 during the last 5-year period. According to incomplete information, this downtrend showed a tendency to slow down, and perhaps level off, in the early 1970's.

By 1970 the multiplier effect of \$1 of exploration in Canada was of the order of 50. This compares well with numbers mentioned by American Metal Climax (AMAX) (1971), in a study presented at a U.S. congressional hearing. AMAX established that, in 1970 dollars and at 1970 metal prices, the metallic Exploration Effectiveness in the western United States was about 80 for the period 1956–1960 (compared with 110 for Canada), 59 during the next 5-year period (compared with 95 for Canada), and 45 during the last 5-year period (compared with 55 for Canada).

In the United States, some reasonably good numbers for uranium exploration are regularly published by a government agency (Grutt, 1975; Klemenic and Sanders, 1976); they indicate that the effectiveness of U.S. uranium exploration has decreased considerably in the last 10 years. The multiplier effect, for the period 1967–1971, is 8, when the discoveries are valued at \$30 uranium. During the next period, 1971–1976, the multiplier effect has decreased to 6 at \$8 uranium and 40 at \$30 uranium.

In general, the metals Exploration Effectiveness in developed countries having a fair mineral endowment and history of exploration is 40–50, about one third of what it was 20 years ago.

TABLE 1.2 Metals Exploration Expenditures, Average Annual Number of Discoveries, Average Annual Value of Discoveries, and Exploration Effectiveness in Canada during the 20-Year Period 1951–1970, in Dollars, at 1971 Metal Prices (after Cranstone and Martin, 1973; Bailly, 1977)

Period	Total Exploration Expenditures, Annual ^a Average in \$Millions (Y)	Discoveries, Annual Average		Exploration Effectiveness ^b (\$ per each \$ of Exploration Expenditure) (X/Y)
		Number of Discoveries	Value in \$ Billions (X)	
1951–1955	28	14	4.4	160
1956–1960	48	8	5.4	110
1961–1965	54	9	5.2	95
1966–1970	98	7	5.4	55

^a For all exploration projects whether successful or not.

^b See Figure 1.3(a) for definition of exploration effectiveness.

TABLE 1.3 Project Effectiveness and Exploration Success Ratio for Metals Exploration in Canada during the 20-Year Period 1951–1970, in 1971 Dollars, at 1971 Metal Prices (after Cranstone, 1973; Bailly, 1977)

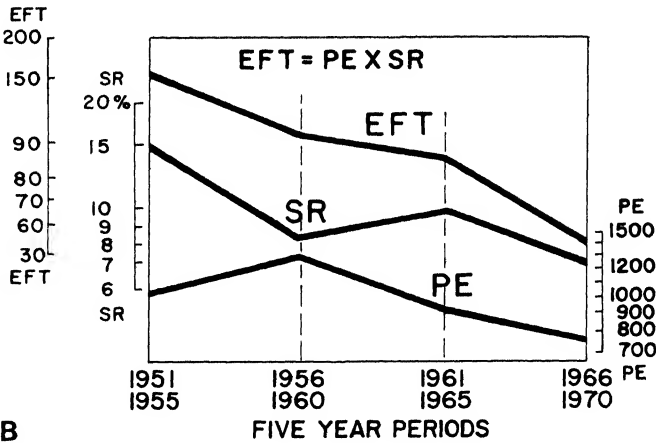
Period	For Successful Projects Only			For All Projects	
	Average per Discovery				
	Value in Millions (A)	Project Exploration Expenditures in Millions ^a (B)	Total Exploration Expenditures in Millions ^b (C)	Project Effectiveness (PE) ^c (A/B)	Exploration Success Ratio (SR) ^c (B/C)
1951–1955	320	0.3	2.0	1050	15.0%
1956–1960	670	0.5	6.0	1340	8.3%
1961–1965	570	0.6	6.0	989	10.0%
1966–1970	770	1.0	14.0	770	7.1%

^a Average expenditures for discovery projects only.
^b Average expenditures per discovery project when exploration expenditures at all projects are taken into account.
^c See Figure 1.3(a) for definitions of these terms.

results of successful metallic exploration The value of the average discovery has years, whereas the exploration expendi- have nearly tripled. If we measure all ex- against the discoveries, we find that the overy to the Canadian mining industry illion per discovery, in the first 5-year during the last period. f the successful projects, Project Efec- ase very much during the 20-year period. of the exploration dollar, however, de- 770—by about one third.

The overall Success Ratio, moreover, decreased from 15 to 7 percent. Today, less than 7 percent of the exploration expenditures in Canada are successful. Figure 1.3(b) summarizes the evolution of our three param- eters; the two contributors to a sizable decrease in Exploration Effectiveness are a minor decrease in effectiveness at successful projects and a much more drastic decrease in Success Ratio. The minor decrease in Project Effectiveness is, in my opin- ion, because the bulk of the expenditures at such projects is for drilling, a technology that has not benefited from any sub- stantial improvement in the last 30 years but which accounts for about one half of exploration expenditures. Other factors

ON EFFECTIVENESS
OF DISCOVERIES
D. FOR ALL EXPLOR. PROJECTS
EFFECTIVENESS
T DISCOVERY
FOR PROJECT
RATIO
FOR SUCCESSFULL PROJ.
FOR ALL PROJECTS
EFT = PE x SR



itions of exploration effectiveness, project ef- ratio. B, Changes in exploration effectiveness

and success ratio in Canada, 1951–1970. [See Figure 1.3(a) for expla- nation of terms and Tables 1.2 and 1.3 for numerical data.]

affecting this decrease in Project Effectiveness are: targets, in general, are getting a little deeper, resulting in increased expenditures; and definition of economic reserves is, nowadays, more complete than in the past—in prior years, exploration was limited to proving just enough tonnage to justify an operational start, whereas today a thorough inventory of discovered resources is usually made before deciding when and on what scale to open a new deposit.

We need cost-effective improvements in drilling, sampling, and analytical techniques in order to decrease the costs of drilling and drill-sample analyses. This would at least slow and, perhaps, even reverse the decline in exploration effectiveness for successful projects.

The main component in the deterioration of the overall effectiveness is the decline in the Success Ratio, in other words, the decreasing percentage of total expenditures leading to discoveries. An investigation of how discoveries were made may suggest ways to increase such efficiency. Of course, one can find ready excuses for the increasing difficulty of finding new ore bodies, but our objective is to improve the situation, not merely to excuse failures.

Figure 1.4 shows the number of mineral discoveries (Albers, 1977; Bailly, 1977; Derry, 1970, 1972, 1976) classed according to the main targeting approach in Canada and the United States. In the United States where, in general, outcrops are more numerous than in Canada and where superficial formations are more weathered and conductive than in Canada, geologic inference has provided steadily increasing flow of discoveries—about 75 percent, whereas geophysical targeting has accounted for 15 percent of discoveries and conventional prospecting and/or geochemistry for 10 percent of the discoveries. Conventional prospecting had nearly died in the United States by 1940 (except in Alaska for uranium), most mineralized outcrops having been found by then.

In Canada (where there is a more general paucity of outcrops, a generally unweathered and resistant bedrock and cover, and

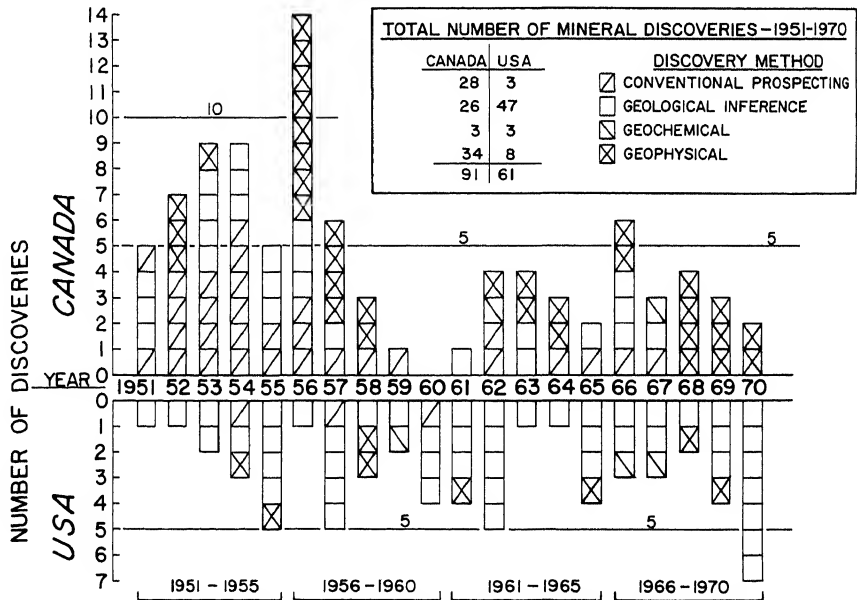
a high proportion of massive sulfide ores having strong magnetic signatures) the advent of efficient geophysical methods after World War II progressively relegated prospecting and geologic inference to decreasing roles as contributors to exploration trophies. Geophysics became the most productive targeting tool by the mid-1950's; before 1950, it accounted for only 5 percent of the discoveries; between 1950 and 1967, it accounted for 38 percent; and between 1968 and 1973, 60 percent. Canada is still in the golden era of airborne electromagnetics. However, the proportion of unsuccessful projects based on geophysical targeting has increased; thus, geophysical targeting must accept its share of the blame for the decrease in exploration Success Ratio. Geochemical exploration surveys began to be used with very limited success between 1950 and 1967; the effectiveness increased between 1968 and 1973, contributing 15 percent of discoveries.

The reliance on geotechnology has caused an atrophy of geological thinking and daring in some members of the exploration community. To quote an unnamed, but reliable consultant in Toronto:

It seems that with the rapid strides in the development of more sensitive geophysical tools measuring more physical parameters and the advent of geochemistry, more mines should have been found. I feel that the development of these techniques has had an inverse effect upon the field geologist or prospector who prefers to sit on his butt and let the instruments do the work.

Canadian results since 1973 indicate that geophysics, unless it can penetrate deeper and be more discriminating, will see its usefulness reduced in Canada. I doubt that the small proportion of geochemical discoveries will increase in the future; although analytical and interpretation methods are improving, too many factors affect geochemical values to suggest an increase in the ore-targeting power of geochemical surveys. One can foresee, for Canada, an increase in geological discoveries because the perceptions of good geological explorationists will continue to receive increasing recognition and will be used to

FIGURE 1.4 Number of mineral discoveries in Canada and the United States, 1951–1970 (after Albers, 1977; Derry, 1972, 1976).



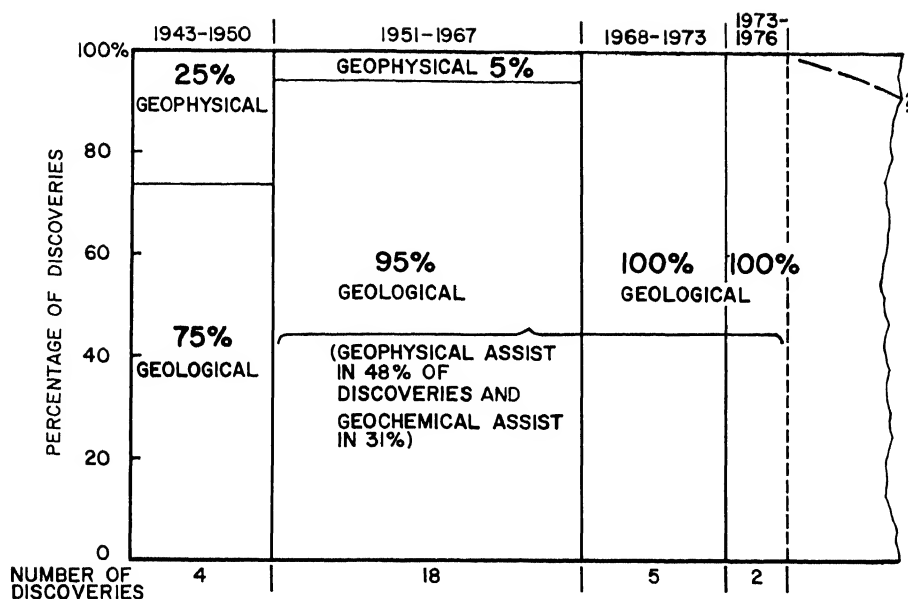


FIGURE 1.5 Method of discovery of commercial porphyry copper deposits in the Western United States, 1963–1976 (Bailly, 1972; 1976b).

greater extent than in the past. The Precambrian Shield areas in the United States will follow the same trends noted in Canada.

In the western United States, exploration for porphyry copper has met with success in the last 14 years—29 discoveries (Bailly, 1972, 1976b). Figure 1.5 shows that the role of geophysics as an instrument of success in porphyry copper exploration has always been minor and now appears to be on the increase. This statement should be qualified by noting that only 100 percent of geologic discoveries were partly assisted by geophysics and geochemistry; however, this was noncritical assistance—not essential strategic targeting. Thus, in spite of the very sizable expenditures for geophysics in the search for porphyry copper deposits, this approach has been relatively unproductive.

Modern porphyry copper exploration in the United States provides a good illustration of the power of geologic extrapolation as a discovery tool. Geologic thinking is without any doubt the deepest penetrating tool, the most effective of our remote-sensing capabilities. Therefore, improvement in geologic understanding of ore deposits and their setting is the most effective way to improve exploration effectiveness. Nevertheless, such indirect exploration will always have limitations caused by the unpredictability of detailed variations in geological settings (Bernard, 1972). Hence, physicochemical detection techniques that have increased sensitivity and penetration also deserve considerable research, as they will continue to be welcome in exploration.

ECONOMICS AND EXPLORATION

The minerals industry, to assure its viability, must make decisions about new and old deposits under time-tested criteria of return on investment. Hence, it is important for industry to work only on those projects that continue to meet ac-

ceptability criteria as the project progresses through the four main steps in a successful exploration program: (1) regional reconnaissance, to (2) detailed reconnaissance of favorable areas, then to (3) detailed surface appraisal of target area, and finally to (4) detailed three-dimensional sampling and feasibility study. For industry, the project turns negative, i.e., when the expected rate of return falls below the minimum acceptable rate of return (this minimum rate is used as the discount factor in calculating the present worth).

The strong negative effect of time delays on the economics of new mineral projects has been described by Bailly (1976a). Using the same examples of a medium-size, underground zinc project and a large, open-pit copper project, one can show that the only type of delay to the project that maintains an acceptable return of 15 percent or more, and maintains a positive net present worth, is to discontinue expenditures before getting deep into the final detailed three-dimensional sampling phase of exploration. Any long delay that takes place after considerable expenditures have been incurred tends to negate any present worth for a new discovery. The logical corollary is that emphasis in geologic research on ore deposits should be focused on those scientific geologic inquiries that give predictive power and discriminant targeting before the three-dimensional sampling phase is reached. Another corollary is that, from an economic point of view it is not reasonable and from a practical point of view it is not necessary to spend much money now for geologic reserves that will be exploited only after 25 or more years.

IMPORTANCE OF GEOLOGIC RESEARCH IN FUTURE DISCOVERIES

The prospector of old used tactical hunches developed and handed down through generations of empirical observations.

Ore was where he found it (De Launay, 1908). During the prospectors' era, earth scientists were not involved in exploration; they were developing theories that were so elegantly general as to be useless for either strategic or tactical exploration purposes. We are now about finished with both the classical prospector and the exciting, but unproductive, academic arguments such as those between "hydrothermalists" and "syngeneticists." Too often these theoretical arguments just confirmed E. F. Hutton's often quoted statement that: "The prejudice of an invented theory has infected the description of a fact." Neither of these two opposite schools of thought gave much assistance in delineating ore targets. Their chief beneficiaries were those who derived intellectual satisfaction from theorizing about where the metals came from and how they were transported; however, regardless of their factual failings to point to likely sites of ore deposition, they did provide apparent rationales for some successful exploration efforts.

In determining where he will seek his next discovery, the explorationist uses predictive tools, which have been improved at an accelerated rate in the last four decades. Today, the exploration community takes for granted some of the most useful and commonly used ore-occurrence and ore-genesis models. However, let us not forget that, although their heritages may be ancient, their useful forms are recent. To illustrate, let us name just a few: (1) the Archean pebble conglomerate-occurrence models for gold and uranium, developed in South Africa and in the Blind River District; (2) the uranium roll-occurrence model developed in the western United States; (3) the sedimentary phosphate-genetic model that has resulted

in new discoveries in Australia, Turkey, North Carolina, and other parts of the world; (4) the zinc-in-carbonate-sediments model developed for the Tennessee deposits; (5) the Missouri lead models, so well explained during the Society of Economic Geologists Viburnum Trend Symposium in 1975; (6) the porphyry copper-occurrence models developed in the southwestern United States; (7) the volcanogenic model for base and precious metal deposits; and (8) the native sulfur associated with gypsum-anhydrite. In several of these cases, occurrence models have been perfected into genetic models that, of course, have greater predictive value than simple occurrence models.

Our ability to prepare useful mineral-occurrence prediction maps—the basis for exploration planning—is continuously improving. In preparing such maps, we use models that describe the conditions that appear to be necessary for the formation of a deposit. However, we also know that even these valuable tools are not sufficient to guarantee ore.

First-generation discoveries were made through empirical observations by prospectors, and second-generation discoveries are made through technical surveys in the vicinity of previous discoveries. For several types of deposits (e.g., sandstone uranium, evaporite-associated sulfur, Archean gold-uranium, komatiitic nickel, carbonate lead-zinc, marine phosphate), we are now starting the third generation of discoveries that are essentially conceptual, based on scientific identification of areas where ore is predicted to occur. The outlook is for increased confidence in the validity of predictions about mineral occurrences. The new confidence can be gained and improved only through continued geologic research on ore deposits.

TABLE 1.4 Applications of Geology as a Scientific Discipline at Different Stages of Mineral Exploration and Development as a Factor of Potential Importance^a

Stages of Exploration and Development	Scientific Geologic Concepts, Hypotheses, Models, and Theories					
	Observations Factual Observations and Documentation		Natural Associations		Hypotheses-Theories	
	Deposits (Maps)	Regional (Maps, Photos)	"Ore Controls" Ore Patterns, Metallotects	Nongenetic Occurrence Models	Genetic Occurrence Models	Geologic Theories of General Scope
Regional appraisal	Minor	Major	Major	Major ^b	Major ^b	Minor
Detailed reconnaissance						
targeting	Major	Major	Major	Major ^b	Moderate ^b	
Detailed surface appraisal of target	Major	Minor	Major	Major ^b	Moderate ^b	
Detailed 3-D evaluation of target	Moderate ^b		Moderate	Minor	Minor ^b	
Mining extraction			Minor	Minor		
Metallurgical recovery			Minor		Minor to major	

^a Potential importance at different stages of exploration.

^b Today's use is much less than tomorrow's potential importance.

Table 1.4 shows how geology as a scientific discipline relates to exploration. Our knowledge of the geology of mineral deposits usable in exploration consists of the following, in order of increasing scientific generalization (Bailly, 1972):

1. Factual descriptions based on observations of deposits and their settings, available as monographs and as geologic maps. The existing maps and monographs are used as the main source of target concepts in today's exploration. That only one third of the United States is covered with geologic maps at a scale suitable for prediction work and that modern geologists do not seem to find the time to prepare thorough descriptive monographs of new discoveries are facts to be deplored. The significance of such maps and monographs in past and future discoveries is too great for their contributions to be absent for long without seeing exploration effectiveness suffer. Today's use, at the three-dimensional evaluation stage, is much less than tomorrow's potential use.

2. Recognized mineral associations and metallotects based on multiple observations that point to patterns to look for, as signs of the possible presence of valuable deposits. These are used during the first three stages of exploration to delineate targets.

3. Mineral deposit-occurrence models that integrate all the metallotects associated with certain types of deposits. Such models are without explicit genetic connotation. Some occurrence models have been named in this report and have been used, to some extent, in exploration. This is an avenue of research that is wide open and that requires much more work. The target hypotheses derived from such models are generated in the mind of the explorer, who makes a plausible case for his postulate that ore may be found where he predicts it to occur.

4. Genetic models give an intellectually satisfactory explanation of depositional environments and deposition mechanisms that are effective in creating certain types of deposit. *Valid genetic models are, undoubtedly, the most potent of all targeting tools.* However, most current genetic models are only primitive hypotheses that are trying to explain occurrence models. Refinements brought by adding to the models the various genetic factors concerning the source and the transportation mechanisms for the mineral components are scientifically significant but as yet of little value in most exploration. They could have a greater value and application in the future.

5. Geologic laws of nature or theories of general scope. These are probably too general to have much value in exploration planning (Krauskopf, 1971) beyond the first steps in regional appraisal.

A new geologic model or hypothesis usable in mineral exploration may affect exploration results only 3 or 5 years after its formulation; prior to formulation, it may have taken several years to go from the first insight to a reliable scientific statement. It takes 5 years, on the average, to conclude a successful exploration project with the discovery of a reserve, and then it takes up to 7 years to get the deposit ready for operation. Thus, it takes about two decades for scientific geologic insights to start affecting mineral production. Geologic research will become an increasingly dominant factor in transforming un-

discovered resources into reserves and future production, but we must recognize that it is a very slow-acting factor. Because of its great potential value to mankind, geologic research thus deserves immediate, patient, and sustained encouragement and support.

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An Explorationist Looks at Research

2

STEWART R. WALLACE
Consultant, Lakewood, Colorado

The ultimate goal of the explorationist is to discover concentrations of minerals of such size, shape, and grade and in such places that they can be profitably extracted from the earth's crust and fashioned into the great variety of materials and products on which modern society is dependent. The insights and clues that guide these efforts along particular lines and lead to certain targets are many and varied. They may range, for example, from details about the composition and texture of specific rock types or the form of a particular rock body to large-scale hypotheses on the composition of the earth's atmosphere 2 billion years ago and the possible influence of this on chemical processes affecting mineral deposition. The tools used in exploration are equally diverse: topographic, geologic, geophysical, and geochemical maps at many scales and descriptive or interpretative models of individual deposits or districts, of ore-body types, and of metallogenic provinces and epochs.

The explorationist does not, however, have complete freedom of choice in scientific endeavors. My short contribution to this volume is not the proper place in which to discuss world geopolitics, domestic environmental problems and legislation, supply and demand of both strategic and nonstrategic commodities, or the human and financial resources of a mineral

company or its corporate goals or areas of special expertise. I simply wish to point out that these factors are critical to the scope and timing of exploration programs and to the selection of prospecting regions and of target size and type. These are very real considerations that limit and restrict both the activities and the ponderings of the geologist.

Ore bodies are the product of one or more cycles of concentration, by a variety of geologic processes, of a particular element or group of elements, and each deposit represents the "culmination" of an unusual series of geologic events involving some of the earth's most complex processes. As a result, ore deposits are extremely rare geologic features. They are distributed sparsely within the earth. To the ancients their occurrence was random; later came the realization that certain types of ore were characteristic of particular geographic areas, and in the recent past this empiricism has been superseded by a steadily improving, but still incomplete, geologic understanding of the gross distribution of ores and types of deposits in space and in time.

Prior to World War II, the literature of ore bodies was largely descriptive, and attempts at explaining their origin were both general and speculative. Although much remains unknown, our

knowledge of the formative temperature and pressure conditions; the sources, volumes, and flow rates of solutions; and the concentrations of elements and isotopes within them is much greater than heretofore. The constraints of this knowledge have led to much more rigorous and definitive concepts of ore genesis.

Ore bodies of the future will be increasingly difficult and expensive to find; accordingly, the better our understanding of known deposits, the more efficient and rational our search for as yet undiscovered ones will be. Our quest for knowledge should continue both in the field and in the laboratory; it should be regional as well as local, and genetic as well as descriptive. The general problems to be solved are as follows:

1. What are the sources of the metals and also of the water, the halogens, the alkalis, and sulfur?
2. What are the "mechanisms" and conditions of mobilization, transport, and concentration of different elements and compounds?
3. What controls deposition?

MAPS AND MAPPING

Geologic maps (and reports), prepared either solely by the U.S. Geological Survey or in conjunction with various professional societies or state agencies, have been the foundation of reasoned exploration as contrasted to the random probings of prospectors.* The maps are available at a variety of scales covering continents down to 7 1/2-minute quadrangle size or smaller. The maps emphasize different features (lithology, structure, bed-rock, surficial deposits, as well as topography and culture). The continental, national, and regional maps are essential for visualizing gross geologic relationships and serve as the initial step in planning an exploration program for as yet undiscovered ore-bearing provinces or districts. On a different scale, quadrangle, or mining district, maps are invaluable for "field orientation" and are the point of departure for more detailed and specialized studies undertaken by the exploration geologist. The importance of *good* geologic maps and compilations to an exploration program cannot be overemphasized.

A good map is always useful, but geologic concepts change, and the mapper's tools continually evolve. Thus, other things being equal, today's product is more accurate, more comprehensive, and more useful than yesterday's. Because of this and because many areas have been geologically mapped only in a reconnaissance manner, it is essential that the government maintain a strong and active mapping (and sampling) program.

The science and art of making a good map require far more than physical labor, cartographic skills, and a knowledge of rocks; they demand discrimination, intuition, curiosity, and persistence in determining not only what the physical rela-

tionships are but what they mean. There is no substitute for experience, and it should be a definite management policy to screen, train, and develop promising personnel who have a demonstrated ability to produce *good* maps. It is my opinion that geologists with the U.S. Geological Survey and state geological surveys have demonstrated competence in producing good maps, and the responsibility for basic mapping should be retained by such personnel and not contracted out. Geologic relationships drawn on a map are the basis for subsequent investigations, and bad geologic maps may be worse than no maps at all.

GEOPHYSICS

There is widespread agreement in the mining industry that the United States should have a complete airborne magnetic survey at a suitable scale. The only differences of opinion are whether it should be done by the government or by private firms on a contract basis and whether the flight-line spacing should be close enough to find ore or sufficiently spread out merely to suggest favorable areas for more detailed examination by the private sector. Results of this work should be available not only as a national aeromagnetic map but as separate overlays at quadrangle scale.

In addition to the application of known geophysical methods, a great deal can be done in the refinement of present, and development of new, equipment and techniques. The objectives of such equipment and techniques are to "see" deeper, with better definition and discrimination and at a reasonable cost.

GEOCHEMISTRY

Exploration geochemistry is perhaps the best example in the field of economic geology of research and development by the government (U.S. Geological Survey), followed by the application and further development by industry. There is still much to be done both in the development of analytical techniques and in their application to identify exploration targets, for example, the investigation of the thermal maturation of indigenous organic matter as a guide to the location of a former thermal halo associated with Mississippi Valley-type lead-zinc (see Chapter 6) or Carlin-type gold deposits or the use of trace platinum-group metal to geochemistry to reveal sulfidation of igneous bodies leading to the development of nickel, copper, and cobalt deposits (see Chapter 4).

There is a great need for three-dimensional sampling of rocks in the vicinity of a variety of known deposits and mineralized districts. The sampling must be carefully controlled geologically and should include the barren country rocks, host rocks, and source rocks. Data sought should include not only whole-rock assays but analyses of selected mineral separates for various metals and indicator elements. The immediate purpose of such sampling programs is to acquire knowledge of the identity and distribution of elements found in abnormally high or low concentrations, the size and location of anomalies, and the

*It is not intended to belittle the prospector or the role that he plays in mineral discovery. His contributions in the past have been great indeed, and they continue to be significant in the initial stages of search and discovery.

magnitude of gradients. From these data one might learn how local enrichment or depletion are related to economic mineralization. In addition, selected sampling over broad areas within and adjacent to metallogenic provinces may disclose the existence and characteristics of systematic or "accidental" heterogeneities in the metal content of the earth's crustal rocks.

FIELD STUDIES

A geologic map is the principal product of a field study. It, together with whatever geophysical or drillhole information is available, is the basis for cross sections, which are the three-dimensional interpretations of a tract of ground. The map is also the fundamental document on which the report is based. Having explained above my particular prejudices about maps, I would like now to cite an example of how comparison of two carefully mapped areas led to the discovery of a major ore body.

At Climax (Colorado), molybdenum mineralization is genetically related to a sequence of "separate" but overlapping to nearly coincident intrusive bodies of silicic-alkalic rhyolite porphyry that constitute a composite stock and dike complex. The original composition and texture of the intrusive rocks ranged from very similar to "identical." In the upper 700 feet of the mine, the alteration of these rocks by hydrothermal events ranged from moderately strong to complete, depending on their location and age with respect to altering solutions that came from different source areas and at different times. Discrimination between the different intrusive rocks and the number and types of hydrothermal events to which they had been subjected, plus a careful mapping and sampling of these features, established the separate age of two partially overlapping ore bodies (upper ore body and lower ore body) and was instrumental in the discovery of a third one (Ceresco ore body).

At Red Mountain, 35 miles to the northeast, the modest-sized Urad molybdenite deposit (14 million tons) was related to an intrusive complex with rocks similar in composition to those at Climax but exhibiting even more phases of igneous activity. Rock textures, however, indicated that the intrusions exposed at the surface had crystallized at a much shallower depth, suggesting, in this environment, the possibility of a deeper ore occurrence. Deep holes drilled on this assumption eventually encountered the large (300 million to 400 million tons) Henderson ore body, approximately 3500 feet below the surface. Clearly the dollar cost of careful geologic study and synthesis was repaid many times over.

In addition to the economic gain, scientific benefits can accrue from studies such as those at Climax and Red Mountain. Having sorted out the field relationships of different rocks involved in one or more hydrothermal events, it is now possible to conduct a variety of experimental and computational investigations on situations and materials having a high degree of relevance to important ore deposits.

LABORATORY AND THEORETICAL STUDIES

The science and the art of economic geology have been dramatically advanced in the past 30 years by the development of

new methods of laboratory study and by the generation of new theoretical concepts. Some specific lines of investigation that have provided important insights into the perplexing relations between ore formation and the rational search for deposits are the study of fluid inclusions, high-temperature solution geochemistry, trace-element content of both ore-related and non-ore-related rock, stable and radiogenic isotopes, and geochronology. For example, present knowledge of fluid inclusions indicates that there is an excellent correlation between porphyry copper deposits and fluid inclusions containing concentrated brines. With respect to stable isotopes, study of hydrogen and oxygen fractionation can reveal whether an argillitic alteration zone originated as a consequence of the oxidation of pre-existing sulfides (as may occur with many types of sulfide deposits) or whether the alteration was formed by hydrothermal fluids (as is an important guide to "bonanza" silver and gold deposits). Radiogenic isotopes of lead have a practical use in exploration in that major massive sulfide and porphyry copper-molybdenum deposits (deposits that originate through processes involving lead homogenization of significant volumes of the crust) tend to contain lead whose isotopic composition reflects the geologic age of the deposit. Thus prospects containing "anomalous" lead are poor bets for massive sulfide or porphyry copper-molybdenum ore bodies. On the other hand, "anomalous" lead is often associated with major uranium and thorium deposits, and in fact may be used to distinguish the sought-for uranium deposits from the relatively uninteresting thorium deposits even before the ore bodies themselves are found. Regarding solution chemistry, adequate knowledge may well indicate in which parts of a dynamic, chemically evolving, hydrothermal system a particular element, for example, copper or silver, might dissolve, migrate, or precipitate. Thus we might be able to predict in which part of a large hydrothermal system the volumetrically small, but economically attractive, ore bodies would be found. Eventually we will have diagnostic criteria to determine whether a given noneconomic prospect represents the promising top, the unpromising bottom, or some distal fringe of an unexposed, possibly economic deposit.

Finally, geochronology is becoming increasingly important not only in studying problems of genesis as applied to a system that has produced multiple ore bodies as at Climax but as a guide in target selection. In Colorado, for example, molybdenite prospects associated with intrusive rocks 35 million to 16 million years before present are much more promising than those related to intrusions of Laramide age (60 million to 70 million years ago); whereas in Arizona, the major porphyry copper deposits are almost exclusively associated with Laramide intrusive rocks.

CONCLUSION

To maintain present mineral production from domestic sources and to increase this rate to meet future demand, the mining industry will need all the help it can get, both technical and political.

In the technical area much can be learned about the formation and localization of ore deposits by continued work and

refinement of data in the different fields of endeavor such as those noted above. In addition, as still newer geologic, geochemical, and geophysical tools and techniques are developed they will need to be tested in and near mineral-bearing areas for background information and calibration. Application and interpretation can then follow rationally.

To achieve the societal goal of adequate mineral supplies will require that industry, academia, and government work together in a spirit of real cooperation, much more closely than

they have in the past. This will not be an easy position to reach, but if done selectively, diplomatically, and gradually it can be accomplished.

Finally, effective use of public lands is essential. Unless much of the public domain is open to mineral entry, and unless regulations are such that mining companies, both large and small, can conduct exploration in an orderly and efficient manner (without undue delay and excessive costs), the potential benefit of successful research will be largely nullified.

II

ORE-FORMATION PROCESSES

Element Dispersion, Element Concentration, and Ore Deposits

3

HEINRICH D. HOLLAND *and* ULRICH PETERSEN
Harvard University

INTRODUCTION

Mineral deposits are volumes that contain one or more substances that can be extracted commercially. Such volumes may be filled with gases, liquids, or solids or with their mixtures. They can exist on bodies other than the earth, although to date economically extractable materials have been confined to the near-surface environments of the earth, and it is unlikely that other parts of the solar system will become attractive as sources of raw materials until colonies are established on the moon or on Mars.

The commercial extractability of elements and compounds depends on the size, shape, location, and constitution of the volume from which they are to be extracted. Most mineral deposits are distinguished by abnormally high concentrations of one or more elements or compounds in a portion of the earth's crust that is amenable to mining. The brines in depressions in the Red Sea are an exception; they form a transition to minable brines in other parts of the world and thence to the oceans as a whole, which now serve as a single, large mineral deposit for several elements. The atmosphere is a similar, large,

homogeneous reservoir, which serves as a commercial source of nitrogen, oxygen, and argon.

Mineral deposits are products of physical, chemical, and biological processes that together have determined the distribution of the elements and their compounds in the atmosphere, biosphere, hydrosphere, and lithosphere. Among these geochemical reservoirs the lithosphere is by far the most heterogeneous. Its heterogeneity is due in part to the operation of the many processes that separate and segregate elements and compounds today and to the operation of these and other processes during much of the earth's history. The search for mineral deposits within the earth's crust should therefore be based on our understanding both of the present-day workings of the earth and of those processes that controlled the distribution of the elements in the distant past, when heat flow was considerably greater than at present, when tectonic processes were possibly different, and when living organisms were either absent or differed greatly from those of the present. This chapter deals largely with the processes that tend to homogenize and diversify the composition of the earth's crust. We shall attempt to give a rather generalized view of the formation of mineral de-

posits as consisting of materials at the extreme end of element distribution patterns, of the manner in which these distributions have been generated and modified during geologic time, and of the implications of these matters for mineral exploration and resource availability.

ELEMENT DISTRIBUTIONS IN CRUSTAL ROCKS

The distribution of several of the major elements in crustal rocks is fairly close to normal* (see, for example, Richardson and Sneesby, 1922). The ratio of the concentration of these elements in their currently mined ores to their mean crustal abundance is typically less than 10. For Fe and Al, the two metals for whose production the largest amount of money is spent annually, this ratio is only approximately 5 and 4, respectively. The cost (not allowing for general inflationary increases) of mining these metals will therefore never rise enormously, because there is no necessity of extracting them from ores whose grade is orders of magnitude less than that of the currently mined ores. The future real cost of extracting Fe and Al from their respective ores will probably depend more on the balance between the increase in the price of energy and the beneficial effects of technological innovations rather than on decreases in the grade of their ores. There are essentially unlimited quantities of readily available rock with concentrations of Fe or Al that are within a factor of 3 of the present ore grade of these metals.

This is not true for the minor elements. Only about 20 elements have crustal abundances greater than 0.01 percent (100 ppm); the remainder includes most of the important metals (such as Cu, Zn, and Pb) other than Fe, Mn, Ti, and Al. The distribution of these elements in crustal rocks is typically far from normal and in general approaches a lognormal† distribution (Ahrens, 1965). Figure 3.1, for example, shows that the distribution of lithium in shales is lognormal or close to lognormal. This is reasonable from a purely intuitive point of view; the probability of finding a rock containing N times the mean concentration of a minor or trace element might be expected to be similar to the probability of finding a rock containing $1/N$ times its mean concentration. The proof of lognormality, however, demands either a sufficiently large data base or a sufficiently thorough understanding of the processes that control the distribution of particular elements. Neither of these proofs is available for most trace elements. Most of the analytical data for trace elements do not extend beyond concen-

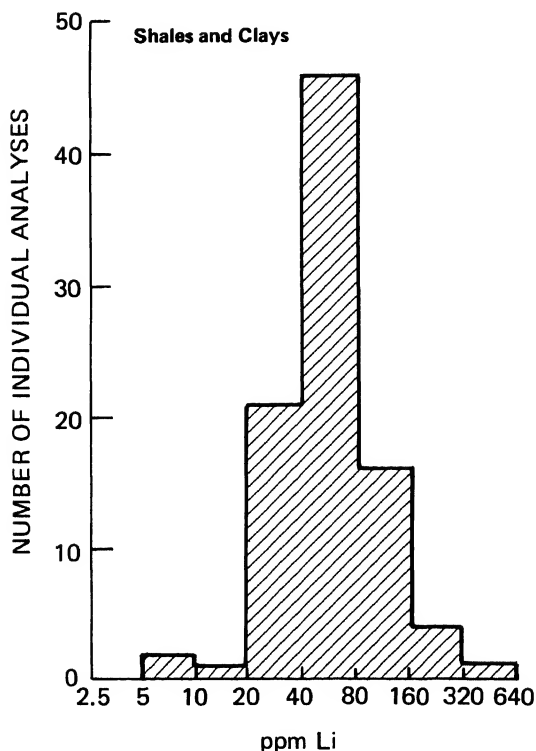


FIGURE 3.1 The distribution of lithium in shales.

trations more than one or two orders of magnitude above or below their mean crustal abundance. The minimum ore grade of most of these elements lies beyond this concentration range (Skinner, 1976a, p. 77), and an uncomfortably long extrapolation is generally required to connect the known crustal dispersion curve of ore metals to their ore grade range. The assumption that the economically important trace metals are distributed lognormally over the entire concentration range between average crustal rocks and ores is therefore poorly based and is probably wrong. As Skinner (1976b) has pointed out, the distribution of ore metals may even be bimodal or polymodal. It is obviously important, both for scientific reasons and for purposes of resource forecasting to define as carefully as possible the actual grade-tonnage relation of ore metals between their concentration in currently mined ores and in average crustal rocks. An attempt to derive such a relationship for U within the United States will be described after a discussion of the major processes that disperse and concentrate the elements.

DISPERSING AND CONCENTRATING PROCESSES

The crustal distribution of the elements is determined by the sum of a multitude of processes that have acted repeatedly since the formation of the earth to disperse and to reconcentrate the elements in the earth's crust. The underlying driving forces

*A normal (Gaussian) distribution is one in which the probability y of a sample containing a concentration x of a given element is given by the expression

$$y = \frac{1}{\sigma\sqrt{2\pi}} \left[-(x - \mu)^2 / 2\sigma^2 \right],$$

where μ is the median concentration of the element and σ is the standard deviation of the distribution.

†The distribution of a concentration x is here taken to be lognormal when the distribution of $\log x$ is normal (Ahrens, 1954).

for these processes have tended to remain the same: the outward transport of heat from the interior of the earth and the input of solar energy. The intensity of these processes has varied with time, and the response of the earth to the input of solar energy has been affected by the origin and evolution of life. The nature and the intensity of the forces that have dispersed and concentrated the elements and their compounds have therefore also varied with time. Nevertheless, the similarity between the most ancient rocks, both igneous and metasedimentary, and their modern counterparts attests to the constancy of earth processes during the past 3.8 billion years (b.y.). Recognition of this rough invariance and of the modulation of earth processes with time has been and will almost certainly continue to be an important ingredient in mineral exploration on a regional scale.

Concentration processes that lead to the formation of mineral deposits can operate in one of two ways: by selectively removing a large fraction of material from approximately average rocks and thereby concentrating one or more elements in the residuum or by direct concentration of a previously dispersed element or compound. Bauxite and lateritic Ni ores formed as a consequence of intense chemical weathering (see Chapter 7) are examples of ores that owe their origins to processes of selective removal. The composition of the earliest metasedimentary rocks (i.e., Holland, 1976) indicates that carbonation reactions during weathering were intense as long as 3.8 b.y. ago, and it therefore seems likely that bauxites and lateritic Ni ores have formed during much of earth history in parts of the continents where chemical weathering was particularly intense.

Most ore deposits have, however, been formed by processes that have brought together previously dispersed materials. These processes have almost invariably involved one or more fluid phases and have been driven by a variety of physical, chemical, and biological mechanisms.

PHYSICAL MECHANISMS

Gravity has played a major role in the formation of placer deposits (see Chapter 8), in the formation of cumulate chromite deposits in ultramafic intrusives (see Chapter 4), in the separation and accumulation of magmatic Cu-Ni sulfide deposits, in driving the flow of hydrothermal solutions and groundwaters (see Chapter 5), and in the separation and accumulation of petroleum and natural gas. In contrast, magnetic and electric forces seem to have played a negligible role in element concentration, except perhaps in the short-range migration of elements in response to natural ground currents.

Since the earth attained essentially its present size approximately 4.5 b.y. ago, the acceleration due to gravity has presumably remained nearly constant for nearly all of the earth's history. There is, however, a fair amount of evidence for considerable changes in the oxidation state of the atmosphere, and it seems likely that placers formed more than about 2.2 b.y. ago contained a higher proportion of minerals that are susceptible to rapid oxidation and dissolution under present-day conditions. The uraninite-containing placers at Blind River in Canada, at Jacobina in Brazil, and in the Witwatersrand and Dominion Reef series of South Africa are almost certainly examples of

such preservation in a less-oxidizing environment. It seems likely that other Archean and early Proterozoic placer deposits exist, and it may be worth looking for ancient placers that contain commercial quantities of base metal sulfides and other easily oxidized minerals. Additional efforts may also be warranted to identify the source regions of the known Precambrian Au-U placers and to search for primary deposits of these elements. It may also be prudent to keep in mind the possibility of finding late Precambrian and Phanerozoic placers of easily oxidized minerals where erosion, transport, and deposition were exceptionally rapid.

CHEMICAL MECHANISMS

Chemical mechanisms of concentration are generally driven by chemical potential gradients, many of which owe their origin to temperature and pressure gradients. This is surely true of mechanisms related to partial melting, fractional crystallization, and liquid immiscibility in silicate and sulfide systems (see Chapter 4). It also applies to the boiling of magmas (Chapter 5) that seems to be largely responsible for the development of porphyry Cu and porphyry Mo deposits and perhaps for the origin of many postmagmatic hydrothermal base- and precious-metal deposits. However, vertical and horizontal temperature gradients within and around cooling intrusives also frequently generate systems of circulating meteoric and/or connate waters. Their circulation patterns, which are frequently discernible in the geometry of their isotopic signatures, have led to the development of major hydrothermal base- and precious-metal deposits. Recent detailed work (Petersen *et al.*, 1977; Birnie and Petersen, 1977; Wu and Petersen, 1977) on the zoning patterns of metals within extinct hydrothermal systems of this type has shown that contours of bulk metal ratios and solid solution compositions can be used to quantify mineralogical changes and to identify the initial front and final edge of the ore deposition interval. This deposition interval is commonly a contorted band with considerable lateral extent relative to its width, as measured from the initial front to the final edge. The zoning contours give information concerning the direction of lateral continuation of the ore band and provide an estimate of the distance to the front of initial saturation. They are, therefore, useful in choosing appropriate and efficient exploration and development strategies.

Zoning patterns also permit a more quantitative treatment of the paleohydrology of such systems by the application of the techniques of hydrologic modeling, which have been pioneered by Cathles (1977), Norton and Cathles (1979), and Fehn and Cathles (1979). It now seems likely that the thermal structure required for the development of major hydrothermal ore deposits is present in the vicinity of many intrusives and within the deeper parts of many volcanic complexes and that the development of ore deposits in such settings depends rather critically on the nature of the hydrothermal flow regimes in such settings. In particular, a relatively large proportion of the total flow must apparently be channeled through a rather small number of pipes and/or fractures. If the flow is too diffuse, mineralization becomes too dispersed and does not reach ore grade.

Zoning studies have demonstrated that some mining districts

resulted from the development of several distinct hydrothermal systems (Petersen *et al.*, 1977) and that the main hydrothermal system in many mining districts is much larger than originally envisaged (Petersen *et al.*, 1977; Birnie and Petersen, 1977; Wu and Petersen, 1977). A study of zoning in the areas of the Mississippi Valley Pb–Zn–barite–fluorite deposits and in the Coeur d'Alene district may well reveal that these deposits owe their origin to hydrothermal systems that were very large indeed.

The chemistry of the transport and deposition of ore minerals in hydrothermal systems is reasonably well understood, although there is still a serious lack of solubility and other thermodynamic data and a virtual absence of data on the kinetics of reactions at elevated temperatures and pressures. Ore deposition is frequently brought about by a decrease in the solubility of ore minerals in the direction of solution flow due to a change in temperature and/or pressure, by reactions between dissolved species within hydrothermal solutions, by boiling, by fluid mixing, and by reactions of solutions with wall rock minerals or with previously deposited hydrothermal minerals. The sum of all of these reactions is frequently complicated. Computer modeling as developed by Helgeson (1968, 1970) has proved particularly helpful in tracing the chemical evolution of hydrothermal systems. As an example, Helgeson's techniques are currently being applied at Harvard University and The Pennsylvania State University to define the chemical changes that accompany boiling in hydrothermal systems, especially the possible effect of these changes on the formation of bonanza Au–Ag deposits and porphyry Cu deposits.

Reactions between oxidized species in solution and reducing agents either along the flow path or in fluids with which mixing can take place are important for the development of many hydrothermal U deposits (see, for example, Rich *et al.*, 1977). The recognition of this fact has had a strong impact on prospecting for such deposits during the past 30 years. The association of hydrothermal U deposits with uraniferous granites has proved similarly important, apparently because such granites generate enough radiogenic heat to drive long-lived hydrothermal systems that are sufficiently intense to produce the associated U deposits (Fehn *et al.*, 1978).

In some hydrothermal systems, seawater is an important component of the hydrothermal fluid. This is true particularly in the Reykjanes geothermal system of Iceland, in submarine geothermal systems such as those discovered near the Galapagos spreading center (Corliss *et al.*, 1979), and in those near 21° N at the crest of the East Pacific Rise. The involvement of seawater in the development of at least some parts of the Japanese Kuroko deposits seems beyond reasonable doubt (Farrell *et al.*, 1978). Whether and what fractions of the metals in these deposits were contributed by magmatic–hydrothermal solutions from depth is still a matter of dispute. It will be most instructive to compare the origin of Kuroko deposits with the origin of the recently discovered sulfide deposits along volcanically active portions of fast-spreading ridges. Whether the mining of such deposits in the deep ocean will ever be commercially feasible is not clear. However, the extensive accumulations of metalliferous sediments near the East Pacific Rise between the equator and 20° S may well be a complement of base-metal

sulfides on the East Pacific Ridge, and thermally anomalous regions in areas of back-arc spreading in other parts of the world ocean may be similarly interesting targets for exploration.

It seems likely that mineral accumulations have formed at numerous places along the 50,000 km of midocean ridges, because ridges are such ideal locales for the circulation of seawater through heated oceanic crust. If such deposits are preserved during the movement of new crust away from spreading ridges, large parts of the deep-ocean floor might ultimately become targets for mineral exploration. The seafloor may then turn out to be of interest for several types of materials in addition to Mn nodules.

Even in the absence of hydrothermal processes, the direct recovery of some elements from seawater, the variety of ocean sediments, and the effects of diagenesis in marine sediments make the ocean basins a major source of mineral commodities. However, with the important exception of the formation of evaporites (see Chapter 8), most of the processes that concentrate one or more elements or compounds to commercial levels in marine sediments involve living organisms and are best discussed under that rubric.

BIOLOGIC MECHANISMS

The biosphere plays and has played a role in the nature and operation of near-surface processes that is out of all proportion to its mass. The disposal of the river input of Ca^{+2} , HCO_3^- , and H_2SiO_4 to the oceans is mediated almost entirely by marine organisms, and the marine chemistry of nitrogen, of phosphorus, and of many trace elements is determined largely by biologic processes. Hence, the distribution of limestones, diatomites, and phosphorites is strongly linked to biologic processes; the success of exploration for phosphate deposits owes much to our understanding of the interplay between the upwelling of nutrient-rich water masses, biologic productivity, and the concentration of phosphate by diagenetic processes (Chapter 8).

The concentration of organic remains in carbon-rich deposits, and the subsequent development of coal, oil, and gas accumulations, is somewhat outside the scope of this report; however, the concentration of significant quantities of metals in black, carbonaceous, frequently petroliferous shales falls within its purview. It is almost inevitable that seawater is normally the source of the metals enriched in these shales (Holland, 1979). Much of the process of concentration must take place not during the lifetime of the organisms whose remains are partly preserved in black shales but during and after sedimentation. Major concentrating mechanisms include extraction from overlying seawater and immobilization by adsorption, precipitation, and coprecipitation with sulfides and oxides. In such sediments the ratio of the excess quantity of a given metal to its concentration in present-day seawater tends to be similar for several enriched elements and is frequently between 1×10^5 and 5×10^5 (Holland, 1979). However, some elements, notably Mo, are underconcentrated in black shales by this criterion, presumably because they are partially remobilized during early diagenesis and diffuse back from marine sediments into the overlying water column.

Some black shales are already of commercial interest and

will probably become progressively more attractive, because they offer the potential for the recovery of several metals as well as the release of energy from the contained elemental carbon and petroleum. Such co-product and by-product recovery is attractive not only in the traditional, direct cost-sharing sense but also because it reduces the overall environmental impact of mining.

The prospective ore tonnages of black shales are very large indeed. A thorough analysis of the distribution of metalliferous black shales within former marine basins, of the mechanisms by which such shales are formed, and of geologic periods that were particularly favorable for the formation of such sediments therefore seems a worthwhile undertaking. The available data suggest that the concentration of the trace metals in seawater has been surprisingly constant during the Phanerozoic era. There are few pertinent data for the Precambrian era.

Although the behavior of trace metals in the Precambrian oceans is largely unknown, it is virtually certain that the marine geochemistry of silica during the Precambrian was quite different from its geochemistry during the Phanerozoic era and that these differences are reflected in the nature of Precambrian sedimentary ores. Cherts associated with the extensive Proterozoic Lake Superior-type banded-Fe formations, which are not related to nearby volcanism, are explained most readily if the concentration of silica in seawater at the time was well in excess of its present-day concentration range. This is readily explained by the absence of silica-secreting organisms during much, if not all, of the Archean and Proterozoic eras and by the requirement that riverborne silica was removed from the oceans at rates that were probably similar to those of the present. A relatively high (30–100 ppm) SiO_2 concentration in the Precambrian oceans might also help to explain the chemistry and mineralogy of the rich, rather curious Zn–Fe–Mn ores at Franklin and Sterling Hill, New Jersey. In areas where hydrothermal solutions emerged into a mildly oxidizing, silica-rich ocean, the mineral hemimorphite $[\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}]$ might have been deposited together with Fe and Mn oxides and/or carbonates. During metamorphism, such mineral assemblages could have been transformed into the assemblages of the famous New Jersey Zn ores (Frondele and Baum, 1974). If this explanation is correct, then it seems likely that other, perhaps unmetamorphosed, ores of the Franklin type remain to be discovered in Precambrian sediments; such ores could have been missed, in part because the physical properties of hemimorphite are rather commonplace.

THE CRUSTAL DISPERSION OF ELEMENTS: THE EXAMPLE OF URANIUM

The crustal dispersion of many trace elements extends from concentrations in the parts per billion (ppb) range to concentrations in the range of tens of percent. Uranium belongs to this group of elements. Volumes up to a few cubic meters may consist of nearly pure uraninite and hence may contain up to about 88 percent of U. In extremely rich portions of mines, U grades can reach values in excess of 10 percent. However, the grade of most U ores today is well below 1 percent; frequently

it is less than 0.1 percent. In the future, rocks containing less than 0.05 percent [500 parts per million (ppm)] of U probably will be commercially attractive (Uranium Resource Group, 1978).

The development of nuclear power depends in part on the future availability of U; there is, therefore, a great need for reasonably reliable estimates of the resource base of U. Such estimates are difficult to make, because most ore bodies of U are small, and because their distribution tends to be erratic at depths of less than 500 m and largely unknown at greater depths. Nevertheless, it is possible to make reasonable estimates of the minimum tonnages of U ore within the range of grades that are currently mined and gross estimates of tonnages between these grades and the concentration of U in average crustal rocks. This is especially true in areas such as the United States where analytical data for the distribution of U are reasonably abundant. Figure 3.2 (Tulcanaza and Holland, in preparation) is an attempt to construct such a distribution curve. The abscissa represents the concentration of U on a logarithmic scale from 0.1 ppm to 10^6 ppm (100 percent). The ordinate represents the estimated number of tons of rock within the upper 1 km of crust below the United States, which has a U content between the indicated concentration limits. (This scale is logarithmic, because the range of tonnages is much too large for a meaningful representation of the data on a linear scale.) The use of this diagram is limited to the roughest of indications of U resources within the United States.

The total mass of rock in the upper 1 km of crust beneath the continental United States is about 2.7×10^{16} tons. The

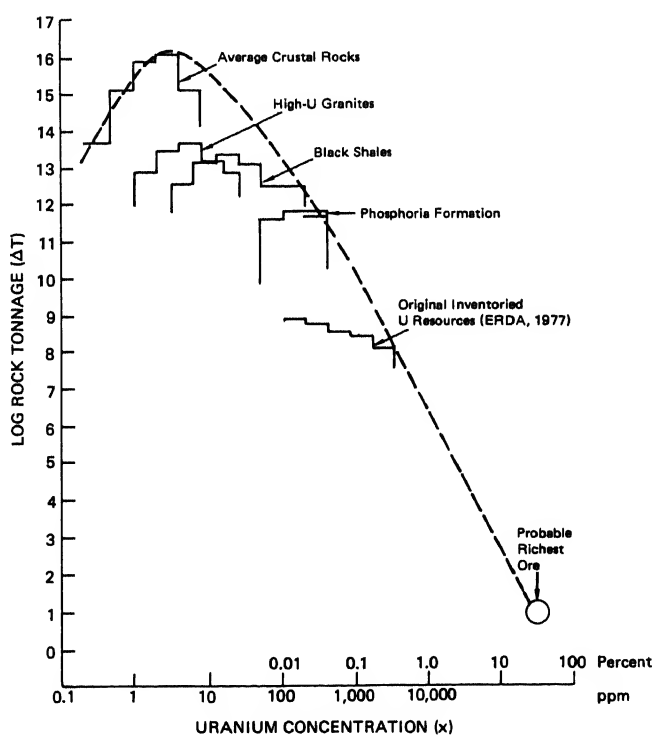


FIGURE 3.2 Grade-tonnage data for uranium in the top 1 km of crust below the continental United States.

tonnage distribution of U in the category of average crustal rocks was derived from this figure, from estimates of the lithology of rocks in the uppermost 1 km of crust, and from the distribution of U in the several rock types. The tonnage distribution in the category of high-U granites is based on data for U in uraniferous granites in the Colorado Front Range, the Boulder Batholith, and the Granite Mountains. The distribution of U in black shales includes units that range in location from eastern Tennessee to Texas and Montana. The Phosphoria Formation of the western United States is used as a representative of phosphatic rocks. Its tonnage greatly exceeds that of other phosphate rocks in the United States. The distribution of grades in the category of original inventoried U resources was taken from an earlier ERDA (1977) report on this subject. Very little high-grade U ore has been mined in the United States. The indicated grade and tonnage of the richest ore is a rough estimate based on conversations with mining geologists.

The several distributions in this figure have different meanings. The grade-tonnage relation for average crustal rock is determined by the area of the United States, by the 1 km depth that was chosen for the calculations, and by the U content of average crustal rocks. The actual contained U in average crustal rocks is therefore almost certainly close to the indicated value in Figure 3.2. The other distributions, however, represent minimum values for the U content in the several categories. Not all high-U granites, black shales, or phosphorites are represented in their respective grade-tonnage curves, because not all rock units in these categories are known or have been analyzed. The category of original inventoried U resources includes only resources that were known when the 1977 ERDA report was written. A reasonably accurate figure for total resources will have to await the results of another century of exploration. The tonnage of probable richest ore is a minimum value for related reason. The true tonnage of U in all but the average crustal rocks categories is therefore surely greater than the tonnages indicated in Figure 3.2. However, because the tonnage scale is logarithmic, the average shape of the distribution curve will probably not be changed dramatically by the acquisition of new analytical data and discoveries of additional U ores.

The data in Figure 3.2 reinforce several impressions.

1. The tonnage of U ores is small compared with the tonnage of U in average or nearly average crustal rocks. This is apparently true of most, if not of all, minor and trace elements (Erickson, 1973). The shape of the U distribution curve, and presumably the curves of many other metals as well, is therefore determined more by the efficiency of the concentrating processes than by element availability.

2. The actual grade-tonnage relation is complex but does not appear to be bimodal or multimodal. The large gap between the dashed envelope in Figure 3.2 and the distribution of U in the category of original inventoried resources is probably in part due to a lack of economic interest and hence an underestimation of the quantity of U in mineralized ground containing only a few hundred ppm of U. The true slope of the grade-tonnage relation for U is critical for energy resource planning.

The much less well-established curves for other commodities are important for economic policy.

3. Phosphorites will almost certainly be the next major source of U in the United States. Uranium as a by-product of phosphate mining can apparently contribute only a rather minor fraction of the projected U needs. If phosphorites do become a major source of U, very large quantities of by-product phosphate should become available for the fertilizer industry.

4. Black shales could become important sources of U, especially if black shales comparable with the Swedish alum shales were discovered and if the simultaneous recovery of energy and the extraction of several metals from black shales becomes a reality.

5. Currently, high-U granites do not look attractive as sources of U.

The significance of the dashed envelope in Figure 3.2 is perhaps debatable. However, it can be used at least to suggest an answer to the question of whether the distribution of U is lognormal over the entire concentration range of Figure 3.2. Figure 3.3 is an attempt to fit lognormal distributions to the envelope. The result is unsatisfactory. At U concentrations in excess of 100 ppm the envelope can be described by the equation

$$\log \Delta T \approx 20.3 - 3.5 \log x,$$

where x is the concentration of U in ppm. The form of this equation is quite different from that of a lognormal distribution;

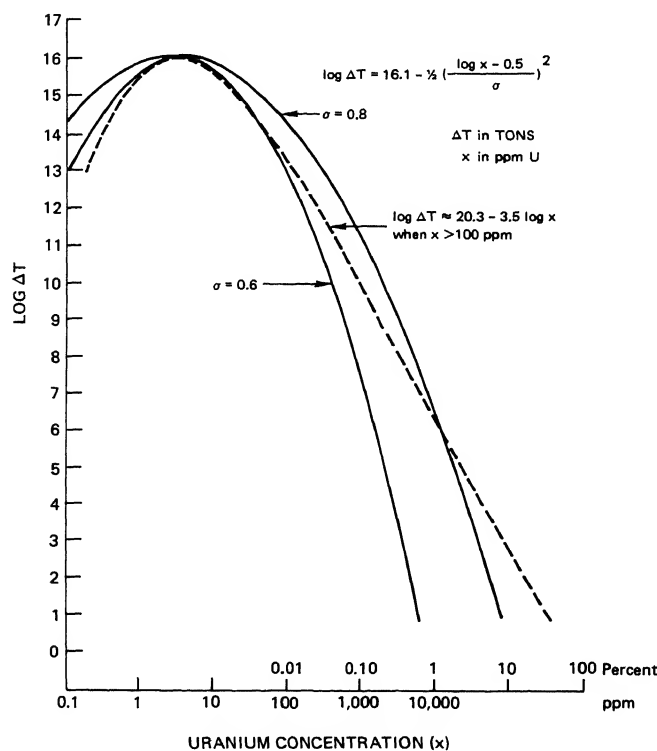


FIGURE 3.3 Attempts to fit lognormal distribution curves to the envelope of the grade-tonnage data for uranium in Figure 3.2.

it is therefore not surprising to find that lognormal distributions can be made to fit either the distribution of U in average crustal rocks if σ is chosen to be 0.6 in Figure 3.3 or the distribution in ores if σ is chosen to be 0.8 in Figure 3.3, but not both. This result should act as a warning if not a deterrent to the use of resource predictions that are predicated on a lognormal distribution of the ore metals.

SOME IMPLICATIONS FOR THE FUTURE OF MINERAL RESOURCES

The grade-tonnage diagram of Figure 3.2 invites a vision of progressively lower ore grades and of ever higher raw-material production costs. Although this vision is probably correct, it may be possible to maintain the rate of increase of the real cost of raw materials at fairly modest levels.

Petersen and Maxwell (1979) have shown that the real cost of most metals proceeds through three stages: an initial period, when production rates are increasing rapidly and unit costs are decreasing because of technological progress and economies of scale; a middle period, when unit costs are nearly constant; and a later period, when the rise in production costs exceeds the effect of economies due to improved technology and increased production. Aluminum has been the most spectacular example of a "new" metal, petroleum and natural gas the most spectacular examples of "new" fuels in the twentieth century. It seems likely that advances in metallurgy and in materials science will bring additional new materials to the fore and that their evolution will serve to slow the increase in the total cost of raw materials.

Recycling and substitution should also be of help, but the stability of energy prices may well turn out to be the single most important requirement for reasonably stable production costs of metals during the next two decades.

Beyond this period the discovery of new ore deposits, particularly deposits that are large and rich, is apt to be of critical importance. The recent discoveries of large, high-grade U deposits in Canada and Australia have followed a renaissance of interest in U and a dramatic increase in the price of this metal. In the United States it may be necessary to revolutionize exploration strategies to make discoveries of similar magnitude. The Precambrian basement under the cover of Phanerozoic sediments in the midcontinent region is a potential target for a variety of major mineral deposits. The discovery of a Witwatersrand-Blind River-Jacobina-type Au-U or U-Au deposit, of a Bushveld-type Cr-Pt deposit, or of extensive deposits of banded-Fe formation could be of considerable importance for the U.S. minerals industry. Smaller exploration targets such as magmatic Cu-Ni deposits of the Sudbury type, carbonatites, and diamond pipes would be more difficult to find, and their pursuit would be harder to justify. Mineral and element dispersion patterns from such ores along or near the Precambrian-Phanerozoic contact might be sought as part of a Continental Scientific Drilling Program (U.S. Geodynamics Committee, 1979).

Deep-ocean mining is apparently becoming a commercial reality. The possibility of mining sulfides on the ocean floor

was discussed earlier, and they are worth keeping in mind for the future. Similarly, the possible presence of ores of Cr and Pt at accessible depths beneath the seafloor deserves some thought, because ores of these metals are characteristically associated with the mafic and ultramafic rocks that dominate the petrology of the oceanic crust.

Finally, it is worth pointing out that a gradual movement to lower grades along the grade-tonnage curve of an element may reach the point where ocean water itself becomes a competitive source for the element. Mn is a case in point, and it may be possible before long to extract several other trace metals from the oceans on a commercial basis. Since the oceans are huge reservoirs of nearly constant grade, grade-tonnage curves such as shown in Figure 3.2 are of only modest economic significance once extraction from seawater becomes attractive. Seawater would become particularly attractive as a source of raw materials if large-scale desalination of seawater were to become economically attractive as a source of water in arid parts of the world.

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Ore Formation Within Magmas

4

ANTHONY J. NALDRETT
University of Toronto

DAVID H. WATKINSON
Carleton University

INTRODUCTION

The principal elements recovered from ores of orthomagmatic origin are Ni, Cu, and Co (recovered from sulfides associated with bodies of mafic and/or ultramafic rock); platinum group elements (PGE) and gold (recovered as a by-product of Ni-Cu ores and as the major product from disseminated sulfides in large, stratiform igneous complexes); chromite (recovered from stratiform igneous complexes and alpine-type ultramafic rocks); V and Ti (recovered from stratiform igneous complexes, Ti also from anorthosite complexes) and Nb, rare earth elements (REE), Cu, apatite, and magnetite (recovered from alkalic, often carbonatitic, ring complexes).

Table 4.1 summarizes the major subdivisions of these ore associations, indicates their relative importance, and gives some idea of the metal contents to be expected in “typical” ore. In this chapter each ore association is discussed in terms of (1) what is known about the genesis, (2) how ideas on genesis have been or can be used in exploration, and (3) what additional research is likely to promote effective exploration in the future.

NI-CU SULFIDE ORES

GENESIS

The Simple Model

The processes involved in the formation of Ni-Cu sulfide ores are summarized in Figure 4.1. They involve (1) partial melting in the mantle to produce a mafic or ultramafic magma; (2) ascent of the magma into the crust (either as an intrusion or extrusion); (3) the onset of magmatic crystallization, either preceded, accompanied, or succeeded by the segregation of an immiscible sulfide liquid; (4) simultaneous partitioning of chalcophile metals into the immiscible sulfide liquid; (5) concentration of the immiscible sulfide liquid, usually by gravitational settling, to form an ore body; (6) crystallization of the ore; and (7) possible redistribution of metals in the ore by hydrothermal or diffusion processes after crystallization.

The key factor is the presence of an immiscible sulfide liquid phase, predominantly composed of iron sulfide. The coefficients governing the partitioning of Ni and Cu between sulfide

V- and Ti-rich intrusions	Stratiformly layered intrusions	wt. % TiO ₂	P	V	TiO ₂
		V ₂ O ₅			
	Bushveld complex	1.4-1.7	<0.05	Maj	Min
	Duluth complex	0.1			
	Allard Lake, Quebec (LacTio)	0.2	<0.01		Maj
	Maggie Mt., Quebec	0.17	0.078	Tr	Maj
	St. Charles, Quebec		3-5		
	P-rich	15	<0.13		
	P-poor	19			
	Sanford Hill, New York	18	Tr	Tr	Maj
	Iron Mt., Wyoming	22	Tr	Tr	Maj
		Nb ₂ O ₅	REE oxides	U	Cu
Nb, P, REE, U, Cu	Carbonatite	0.7	Min	—	—
		0.45	—	—	—
	Oka, Quebec	Min	Min	Min	0.7
	Palabora, S.A.				
	Various Ugandan complexes	0.2	—	—	—
	Mountain Pass, California	—	5	—	—
	Khibina, U.S.S.R.	—	Maj	—	—
	Ilimaussaq, Greenland	—	Min	0.02-0.3	—

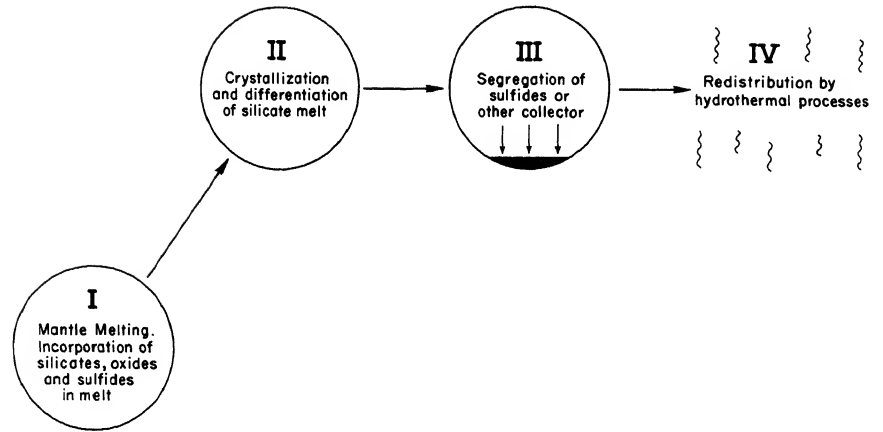


FIGURE 4.1 Four stages in the formation of a magmatic sulfide ore.

and silicate melts are such that, provided the immiscible sulfide liquid is brought into contact with a sufficient quantity of typical mafic or ultramafic magma, and then concentrated, an economically interesting deposit will result.

The Petrotectonic Setting of Ni-Cu Sulfide Deposits

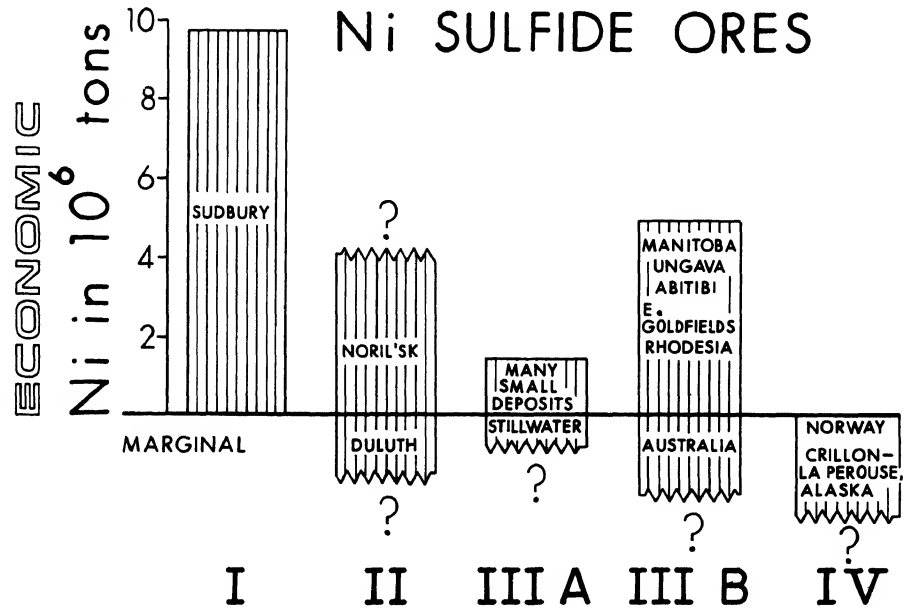
Because a close relationship exists between Ni-Cu sulfide deposits and specific igneous rock types, and because the generation and emplacement of most igneous rocks are related to the specific tectonic environment into which they are emplaced, it is convenient to discuss these deposits in terms of their "petrotectonic" setting.

The great majority of economic concentrations of Ni-Cu sulfide occur in four such settings (Figure 4.2): the gabbro-astrobroleme environment (I), the intracontinental rifting-flood basalt

setting (II), and two settings in Precambrian greenstone belts—those involving synvolcanic tholeiitic mafic magmatism (IIIA) and komatiitic ultramafic magmatism (IIIB). A last setting, that of syntectonic, mafic magmatism within Late Proterozoic and Phanerozoic orogenic belts (IV), accounts for a much smaller portion of total Ni and Cu.

Astrobroleme Studies of lunar meteorite craters indicate that igneous magmatism can be initiated by impact and may be localized within the impact structure. The discovery of shatter cones and shock deformation lamellae in country rocks has led a majority of (but not all) workers in the Sudbury area to accept an impact origin for the Sudbury structure and to interpret many of the previously enigmatic aspects of the geology in terms of this hypothesis. It is proposed that the impact of a meteorite weakened the crust beneath the present Sudbury

FIGURE 4.2 Diagram illustrating the relative importance of different petro-tectonic settings with respect to Ni sulfide ores. I. Noritic rocks associated with an astrobroleme. II. Flood basalts and related intrusions associated with intracontinental rifting. IIIA. Tholeiitic magmatism in Precambrian greenstone belts. IIIB. Komatiitic magmatism in Precambrian greenstone belts. IV. Synorogenic mafic intrusions in Phanerozoic orogenic belts.



Basin and that pressure release accompanying this process triggered the generation of a mafic melt in the mantle that rose through the zone of weakness to intrude the impact structure.

Intracontinental Rift Association In the case of two important nickel sulfide concentrations, large-scale continental rifting has allowed flood basalt-type magma to ascend into the crust, to come into contact with sulfur-bearing sediments, and to assimilate some of the sulfur, thus giving rise to immiscible sulfides. Assimilation of Devonian gypsum and anhydrite is indicated by sulfur isotope ratios in Triassic feeders for Permo-Triassic flood basalts in the Noril'sk area (Godlevski and Grinenko, 1963), whereas isotope data suggest that sulfides in the Virginia formation may be the source of much of the sulfur in the Duluth complex ores (Mainwaring and Naldrett, 1977).

Tholeiitic (Gabbro-peridotite and Gabbro) Association in Orogenic Belts Deposits in this class include those of the Pechenga camp in the Cola Peninsula of the Soviet Union, those of Lynn Lake and Montcalm in Canada, and Carr Boyd in western Australia. At Pechenga, much of the ore is localized at the base of layered intrusions. In the latter three cases, the sulfides appear to occupy discordant pipes or fractures within their host intrusions and, presumably, have been mobilized into their present situation after an initial stage of concentration by gravitational settling.

Komatiite Association Komatiite magmatism forms an important part (in some cases up to 10 percent of the total volume of mafic volcanic rocks) of Precambrian volcanic belts. Geologic evidence indicates that although komatiitic lavas commonly contain olivine phenocrysts, the liquid portion of these lavas, exclusive of the phenocrysts, contains up to 33 wt. % MgO, indicating that extrusion temperatures were as high as 1650°C. Peridotitic komatiites are those komatiites containing more than 20 wt. % MgO in the liquid; they crystallize with a distinctive fabric of skeletal olivine (spinifex texture). The MgO-rich liquids are thought to be the result of unusually high degrees of partial melting of the mantle and appear to be most common in the Archean, possibly because of higher geothermal gradients thought to have existed at that time.

Moderate-sized (1×10^6 to 5×10^6 tons), high-grade (3 percent Ni) sulfide ores occur at the base of flows of peridotitic komatiite, particularly the more magnesian ones. The sulfides occur in footwall embayments that are the result of faulting contemporaneous with extrusion of the komatiites; the embayments may have riffled out and concentrated sulfides from the flows passing across them. Large (40×10^6 tons) concentrations of moderate-grade (2 percent Ni) and much larger (260×10^6 tons) zones of low-grade (0.45–0.6 percent Ni) Ni sulfides are found associated with intrusive dunitic lenses that are commonly found in areas characterized by komatiitic extrusive rocks.

Genesis of Sulfide-Saturated Magmas

The presence of many ore bodies at the base of their host intrusions suggests that gravitational settling of immiscible sulfide liquid is the most important mechanism in sulfide concentration. Most of the exceptions to the rule of basal control

occur in areas that have undergone deformation (e.g., Thompson, Manitoba; Shebandowan, Ontario), where plastic flow of sulfide, perhaps coupled with dissolution, transportation, and reprecipitation via aqueous fluids, has occurred. In order that sulfides be concentrated effectively as a result of gravitational settling and an ore deposit form, some process must cause a significant amount of sulfide liquid to become immiscible at a particular stage in the crystallization of a silicate magma—much more than that segregating as a normal consequence of magmatic crystallization. This excess of sulfide can then settle to form a body that is relatively undiluted by silicate grains. Such a process may be related to those governing the solubility of sulfur in silicate melts.

Experimental work suggests that the solubility of S in a mafic melt can be reduced by the following:

- **Oxidation.** (MacLean, 1969), converting Fe^{2+} (with which sulfur associates in the melt) to Fe^{3+} (with which it does not associate).

- **Silicification.** Irvine (1975) has pointed out that the addition of silica to a mafic magma depresses the sulfur solubility and has suggested that the assimilation of a large amount of felsic country rock, fractured and heated by meteorite impact, may account for the abundant concentration of Ni sulfide ores at Sudbury. The siliceous nature of the Sudbury norite lends support to this hypothesis.

As an alternative explanation for the excess of sulfide liquid, we have already pointed out that assimilation of sulfur has been demonstrated to be of importance in the Duluth complex and at Noril'sk.

Naldrett (1973) and Naldrett and Cabri (1976) have suggested that the association of Ni sulfides with peridotitic komatiites is due to these magmas being derived from a level in the Archean mantle that was particularly rich in sulfide melt. There is a possibility (Groves *et al.*, 1979) that some of this sulfur is derived from assimilation of country rocks, although no direct evidence exists in the form of S isotope ratios significantly different from those typical of the mantle, or remnants of partly resorbed xenoliths of country rock. Whatever the ultimate source of S, geologic evidence indicates that the komatiitic lavas were saturated in sulfide melt at the time of extrusion so that the sulfides (and therefore the metals) in any given ore deposit were not concentrated solely from the volume of rock immediately overlying the deposit but from a much larger volume of magma.

In summary, magmas anomalously rich in sulfide can be produced directly from the mantle, can be produced by the addition of country rock S to magmas intruding into the crust, and can be produced by the silicification or oxidation of undersaturated magmas.

Partitioning of Metals into Sulfide Melts and the Composition of Ores

Recent work by MacLean and Shimazaki (1976) and Rajamani and Naldrett (1978) permits the modeling of the composition of magmatic sulfides in equilibrium with silicate magmas. The equation relating Z_m (final concentration of metal m in silicate

magma), $D_m^{s/l}$ (partition coefficient of metal m between silicate and sulfide liquids), and Y_m (final concentration of metal m in sulfide liquid) has the form

$$Y_m = D_m^{s/l} Z_m.$$

Normally, data that are available require one to model the composition of an ore knowing the initial concentration of the metal in a silicate melt (X_m) before the sulfide melt has reacted with it and not the final concentration after reaction. In this case, the final concentration in the sulfide melt depends not only on the composition of the silicate magma but also on the relative amounts of silicate magma and sulfide liquid reacting. Campbell and Naldrett (1979) have shown that this is governed by the equation

$$Y_m = X_m D_m^{s/l} (R + 1) / (R + D_m^{s/l}),$$

where R is the magma/sulfide ratio by weight.

They have applied this equation, together with appropriate values of D taken from Rajamani and Naldrett (1978), to illustrate that a typical komatiite magma containing 27 wt. % MgO, 10 wt. % FeO, 1200 ppm Ni, 45 ppm Cu, and 65 ppm Co can give rise to sulfides with compositions similar to that typically associated with komatiite lavas (22.6 wt. % Ni, 1.0 wt. % Cu, and 0.26 wt. % Co) at an R value of 2500. Modeling, assuming an R value of 50, gives rise to sulfides containing much less of these metals (3.96 wt. % Ni, 0.16 wt. % Cu and 0.16 wt. % Co). Campbell and Naldrett (1979) have suggested that localized assimilation of country rock sulfides can produce a system with a low content of the valuable metals. Metals with similar values of $D_m^{s/l}$ will vary in a similar manner and their ratios to one another will not change with variations in R , whereas metals with markedly different values of D will vary differently and show marked variations in ratio with R . Thus, in the case of deposits associated with gabbroic magmas, for which the effective values of $D^{s/l}$ for Cu, Ni, and Fe are about 250, 275, and 5, respectively, little change will occur in the Cu/Ni ratio as a function of R , but major changes will occur in the Cu/Fe and Ni/Fe, both decreasing markedly as R decreases.

GENETIC MODELS AND THEIR USE IN EXPLORATION

Some of the genetic concepts outlined above have been used to guide exploration for many years, whereas others have great potential use (see next section). Concepts and axioms in active use by all exploration geologists include the following:

- Ni-Cu deposits are almost universally associated with mafic and ultramafic rocks, which can often be located by airborne magnetic surveys.
- The relationship of ore to basal contact is an empirical observation and is one of the principal arguments in favor of a magmatic model that incorporates gravitational settling of dense sulfide melts. The model has been established so well that it has become customary to determine the stratigraphic base of an igneous body and concentrate most exploration there.
- Certain deposits are related to petrotectonic settings. Archean greenstone belts are particularly important as they con-

tain peridotitic komatiites. Although, in the past, rifting may not have served to guide much exploration outside of the Soviet Union, it is now recognized that rifting is often accompanied by magmatic activity and at Noril'sk and Duluth has allowed mafic magmas to come into contact with S-rich sediments. In some cases the sediments themselves resulted from the rifting (e.g., evaporites in the early development of aulacogens).

- The relationship of mineralized ultramafic bodies to stratigraphy is extremely important in certain areas and is an empirical observation rather than the result of deduction from genetic principles. Komatiites occur in the lower parts of the mafic to felsic volcanic cycles that characterize many greenstone belts. Specific horizons within a given komatiite succession form particularly important ore targets for reasons not fully understood. These horizons are sometimes rich in Fe sulfide-bearing sediments (e.g., Kambalda—Ross and Hopkins, 1975), suggesting that S assimilation may have played a role, although direct evidence for this hypothesis is lacking. Alternatively, the horizons may represent ultramafic rocks derived from the tapping of a particularly S-rich portion of the mantle. The stratigraphic approach has also proved important in exploration for komatiite-related deposits in Rhodesia and Canada and in the search for tholeiite-related deposits at Pechenga, U.S.S.R.

- Certain types of mafic and ultramafic rocks that lack significant, associated Ni-Cu sulfide ore bodies appear to be unfavorable hosts (Naldrett, 1973). These consist of (1) Alpine ultramafic bodies, including both cumulate and metamorphic (mantle)-textured portions of ophiolite complexes, (2) Alaskan-type ultramafic rocks, and (3) those mafic and ultramafic rocks associated with alkalic complexes. The belief that metamorphic-textured harzburgites and lherzolites in ophiolite complexes represent portions of the mantle led, on the basis of genetic ideas, to the conclusion that significant concentrations of magmatic sulfide are unlikely to have had the chance to form within these rocks. The rarity of deposits within Alaskan-type rocks, or in the cumulate portions of ophiolite complexes, remains, however, enigmatic from a genetic point of view.

GENETIC MODELS IN EXPLORATION AND AREAS FOR FUTURE RESEARCH

Recognition of Sulfide-Saturated Magmas

When faced with the task of evaluating a mafic or ultramafic body as an exploration target, one of the first questions that an exploration geologist must answer is whether the magma or a portion of the magma responsible for the body was ever saturated in S. (1) The demonstration that many important deposits result from S assimilation should lead one to investigate whether the magma could have come into contact with sulfide or sulfate deposits in the country rocks during ascent from its source. (2) The experimental demonstration that oxidation or silicification may result in the "salting-out" of immiscible sulfides should lead one to question whether there is evidence that either of these processes was active throughout or within a particular portion of the body being considered.

Any of these aspects might lead to the conclusion that a mafic or ultramafic body had a reasonable chance of becoming saturated in sulfide but will not, with any certainty, answer the

question of whether it actually became saturated. A number of approaches have been made recently to answer this question, some with little evidence of success, others showing considerable promise but requiring testing in the field.

At first sight it would seem logical that the best method of recognizing a sulfide-saturated magma would be to determine the sulfur contents of rocks thought to be representative of the initial magma of the igneous body and then to compare these with experimentally based estimates of the S saturation level expected in magma of similar composition. This approach has not proved successful, partly because of the difficulty in identifying rocks representing quenched magmas but largely because of the extreme mobility of sulfides. They may be lost as a result of oxidation in the case of subaerial lavas, reaction with seawater in the case of submarine lavas, or grossly redistributed during low-grade metamorphism in the case of both intrusive and extrusive rocks.

It is possible to model the crystallization of sulfide-free and sulfide-saturated silicate melts if one knows (1) the partition functions of all relevant elements between silicate melts, silicate minerals, and sulfide melts; (2) factors governing the solubility of S in silicate melts; and (3) if one assumes that the separating phases are in equilibrium with a large volume of silicate melt. Preliminary attempts (Duke and Naldrett, 1978) using peridotitic komatiite compositions suggest that after 10–20 percent crystallization there is a major difference between the Ni content of the residual silicate liquid in the case of magmas that have precipitated olivine alone as compared with those precipitating olivine and simultaneously segregating a sulfide liquid. This difference also shows up in the Ni/forsterite ratio of the crystallizing olivine. The difference in behavior is due to the great preference of Ni for the sulfide phase ($D_{Ni}^{S/L} = 100\text{--}300$), and the magnitude of the difference is such that sulfide-saturated, komatiitic magmas should be clearly distinguishable from those that are unsaturated. When applied to gabbroic magmas, the magnitude of the difference between the sulfide-saturated and sulfide-unsaturated cases is less, and distinctions involving Ni will be less clear. However, some elements such as Pt and Pd are believed to have much higher $D^{S/L}$ values than Ni, and preliminary modeling indicates that these elements are much more sensitive to the separation of sulfide melt and are likely to indicate clear distinctions between saturated and unsaturated gabbros.

To attempt modeling of the type referred to above with confidence, we need a much better understanding of how S interacts with a silicate melt as a function of T, P, $f O_2$, $f H_2O$, and other compositional parameters. We also need a thorough understanding of the chemical interaction (crystal chemical, thermodynamic, and kinetic) of major, minor, and trace (particularly Ni, Cu, Co, PGE) elements with silicate melts and their partitioning into sulfide melts. Available data on these points are rudimentary and at present permit only crude modeling.

Recognition of Parts of Intrusions Exposed to the Scavenging Action of Sulfides

An assumption made in the “rationale” for the modeling discussed above was that the separating phases, including the

sulfide melt, should have reached equilibrium with a sufficiently large mass of silicate magma in comparison with their own masses so that the magma did not become significantly depleted in those metals concentrated in either sulfide melt or olivine. Here we discuss the implications of an “anomalously large” amount of sulfide melt reacting with a given amount of silicate magma. Figure 4.3 illustrates the interrelationship between the magma/sulfide ratio (R), the metal content of the silicate magma, and values of $D^{S/L}$. Where D is in range 100–270, R can be as low as 10^4 without significant reduction in the metal content of the magma, but where D is 1000, R should approach 10^5 .

In basaltic magma, values of D for both Ni and Cu are of the order of 250. If an intrusion has undergone a local addition of sulfide, perhaps due to assimilation, the resultant sulfide melt may be concentrated as an ore zone. It follows from Figure 4.3 that if the mass of magma that the sulfide melt has had an opportunity to react and approach equilibrium with is less than 500 times the mass of sulfides, this local portion of the intrusion will be recognizably depleted in Ni and Cu (metal contents will have fallen to less than 50 percent of background value in magma and, in the case of Ni, in olivine crystallizing from this portion of the magma) and extremely depleted in elements with values of D higher than those of Ni and Cu. If the ore body consists of 50 percent sulfide, a simple mass-balance calculation involving a zone of reacted magma in sharp contact with unreacted magma (i.e., ignoring any possible diffusion) indicates that the surrounding depletion aureole can be expected to be 150 times the size of the ore body.

Greater amounts of localized S assimilation, leading to lower values of R , will, in theory, increase the difference between the anomalous area and the general background in the intrusion, making the anomaly easier to identify. However, metal levels in the magma should be directly proportional to metal

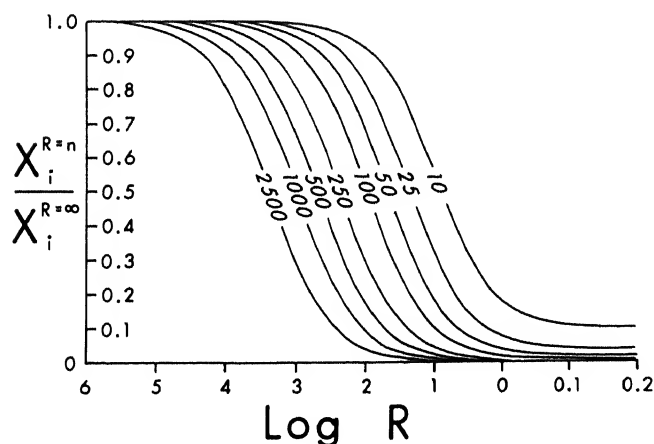


FIGURE 4.3 Relationship between metal content of silicate magma after reaction with a certain amount of sulfide ($X_i^{R=n}$) to the metal content before reaction ($X_i^{R=\infty}$), the ratio of mass of magma to mass of sulfide (R), and the distribution coefficient between sulfide and silicate ($D = \text{wt. \% metal in sulfide phase/wt. \% metal in silicate phase}$) shown as numbers on curves.

levels in the ore body. A 50 percent lowering of the Ni and Cu content of the magma, as envisaged above, will mean that the tenor of the sulfides in the ore will also be reduced by 50 percent, leading to Ni concentrations in the range of 2.5–3 wt. % and perhaps slightly lower concentrations of Cu in a typical, gabbro-hosted deposit. To reduce this to absurdity, a marked depletion anomaly, to a very small fraction of background, would indicate the presence of an ore body containing metals so far below the norm as to be worthless except for its Fe and S. There will, however, be a useful range of *R* values within which an anomaly will be detectable and the ore deposit still viable.

Modeling of the kind discussed above depends again on knowledge of the partition coefficients (we have little information on $D^{S/L}$ values for PGE). Furthermore, it is unlikely that the natural situation would have been as simple as that assumed in our discussion. Diffusion of chalcophile metals through the silicate melt toward centers of sulfide assimilation may also have been important, and we have little data on diffusion rates of metals in mafic silicate melts with which to evaluate the role of diffusion.

Much of the confirmatory evidence of S assimilation has come from S isotope studies. Our understanding of the behavior of S isotopes during assimilation is rudimentary. Fractionation is not usually assumed to occur during assimilation. This is probably true if S enters the silicate melt as S^{2-} . If, as is likely, water is also assimilated, H_2S and HS^- may also form. Furthermore, if a vapor phase forms, strong fractionation of the lighter isotope ^{32}S into the vapor may take place. Some "ex-contact" vein and disseminated ores at major Ni camps (e.g., Noril'sk—Smirnov, 1966) suggest that a fluid has been involved in their deposition, although it is uncertain as to whether the fluid existed before or after consolidation of the magma.

Understanding of the Behavior of Sulfides During Metamorphism

Limited work on mechanical properties of sulfides as a function of pressure and temperature suggests that they are likely to behave plastically at much lower pressure and temperature than the silicates with which they are associated. Field studies indicate that plastic behavior may have played a role in formation of some of the western Australian deposits (Groves *et al.*, 1977). Combined laboratory and field studies are required to define at what metamorphic grade plastic mobility might become significant enough to permit the migration of sulfides away from their original position.

Zoning in the ratios of Ni–Cu–Fe observed in many presumed magmatic ores cannot be explained on purely magmatic grounds (e.g., Noril'sk—Smirnov, 1966; Sudbury—Naldrett and Kullerud, 1967; Cowan, 1968), suggesting that postmagmatic movement of metals must have occurred. To date we have few data on the solubilities or diffusivities for metals such as Ni, Cu, Pt, and Pd on which to base explanations of these observations or with which to predict their significance with respect to ore genesis.

Field Studies

All the opportunities outlined above are based on models of ore genesis that we believe to be realistic. Proof rests in (1) careful field observation of ore deposits and their geological setting, (2) the testing of the models, and (3) their modification or replacement by superior models where necessary.

PGE ORES IN STRATIFORMLY LAYERED INTRUSIONS

The Merensky Reef in the Bushveld complex is the type example of this class of ore deposit, although other strata-bound zones within the Bushveld (in particular the UG1 chromite zone) and the important concentrations within the Stillwater complex, Montana; the Great Dyke of Rhodesia; and, to a lesser extent, the Lac des Iles complex of northwest Ontario constitute important resources.

The following characteristics are based largely on the Merensky Reef but apply to a greater or lesser extent to the other deposits mentioned:

- Association with large intrusions.
- Occurrence at breaks in the sequence of magmatic crystallization, i.e., at the base of macrorhythmic units, resulting from crystallization from fresh magma.
- Association with weak accumulations of sulfide, although metals are commonly present as other minerals in addition to sulfides.
- Correlation between mineralization and coarse-grained, pegmatoidal variants of the host intrusion in many cases.
- Association with hydrous alteration of adjacent silicates in some intrusions. The separate PGE minerals appear to occur in late-stage structures, cross-cutting both Fe–Ni–Cu sulfides and silicates.
- Occurrence in the Bushveld complex below zones of tightly packed plagioclase crystals. Vermaak (1976) has suggested that the zone capping the Merensky Reef is the result of plagioclase floating so that the magma beneath the plagioclase mat has crystallized in isolation from the main body of overlying magma.

GENESIS OF PGE DEPOSITS

The close association between weak sulfide disseminations and PGE has led most workers to accept that sulfides act as the main collector of the platinum group metals. Naldrett and Cabri (1976) point out that there are problems with applying the simple Ni sulfide model of sulfide segregation and gravity settling to account for disseminated PGE ores. They point out that if PGE concentrations in a wide range of magmatic ores are recalculated on the assumption that the metals originated entirely in the sulfide phases, the Pt and Pd of these sulfides (and therefore the original sulfide liquid) range up to 2 and 3 ppm, respectively, in most magmatic sulfide ores but up to 260 and 110 ppm, respectively, in the Merensky ores and up to 500 and 2000 ppm, respectively, in the Stillwater ores. Because values of $D^{S/L}$ for PGE in magmas such as that responsible for

the Bushveld are unlikely to be different from those, for example, in the Sudbury magma, one is forced to conclude that the Bushveld magma must have been approximately 100 times richer in PGE than typical gabbroic magmas, and the Stillwater magma 250–500 times richer. At our present level of understanding, it seems unlikely that concentrations would have been that high.

In response to difficulties of the kind just discussed, some authorities have suggested that chromite acts as a collector for PGE, with subsequent exsolution of the PGE either as alloys or in ways leading to combination with adjacent sulfides and arsenides to produce other typical PGE minerals. Despite a great deal of work on this suggestion, no confirmatory evidence has been developed other than the presence of high PGE values in association with chromite.

Hiemstra (1979) has suggested that Fe–Pt alloys precipitated directly from the Bushveld magma and settled to form the PGE concentrations in the Merensky and UG2 horizons, although he has not demonstrated conclusively that such alloys would be stable at magmatic temperatures under prevailing values of fO_2 .

Other workers have suggested that observed high concentrations of Pt-group metals are due to their emplacement by hydrothermal fluids. This process does not appear to account for the remarkable strata-bound nature of the Merensky Reef and other horizons, although hydrothermal fluids must have been active at some time to account for the associated hydrous alteration.

C. F. Vermaak (Johannesburg Consolidated Investment Company, Ltd., personal communication) has suggested that an initial layer of sulfide might become enriched in PGE subsequent to its formation as a result of coming into contact with magmatic fluids ascending vertically through an accumulating crystal pile. This suggestion is compatible with the gradual recognition by many workers that as a thick pile of crystals accumulates in a large layered intrusion, these crystals will deform and rotate under the superincumbent load to produce a much denser packing; during this process, liquid trapped interstitially will be squeezed out and will percolate upwards. As the liquid moves upwards, it will continue to crystallize, forming postcumulus olivine, pyroxene, and plagioclase in the rocks through which it is passing, thereby becoming enriched in constituents (including PGE) that do not find a ready home in the adjacent silicates. If the enriched liquid comes into contact with a layer of sulfide, PGE may displace Fe and enter into solution in the sulfides, thus enriching them greatly. The efficacy of this suggestion depends on the correctness of the assumption that PGE do not substitute readily into silicates and also on the demonstration that there is a considerable thickness of sulfide-free cumulates below the mineralized horizon from which liquid can be displaced. Contradictions exist as to PGE levels to be expected in silicates, and the presence or absence of sulfides in rocks below such horizons as the Merensky and UG2 has yet to be clarified.

In summary, our understanding of the genesis of ores of this type is far from complete. It would appear, however, that a few generalizations can be made.

- Intrusions in which large thicknesses of crystal cumulates have developed are necessary for their formation.

- These intrusions should have been unsaturated in sulfide during much of their early crystallization; otherwise the segregation of sulfides would have depleted the residual magma and the interstitial trapped fluids in PGE, such that high concentrations of these metals would never have developed.

- After a considerable thickness of sulfide-free cumulates has developed, some perturbation in the crystallization process, such as an increase in fO_2 , mixing with a magma of different composition, or the precipitation of a new liquidus phase, should result in a sudden, if minor, saturation of sulfide in the magma so that these settle to form a strata-bound layer.

OPPORTUNITIES FOR PRODUCTIVE RESEARCH

From the preceding discussion, clearly our understanding of these ores and hence our ability to predict the combination of factors in a magma chamber leading to their formation are severely hampered by our lack of knowledge of (1) how Pt-group metals partition among the precipitating phases in mafic magmas and (2) the role that late magmatic or hydrothermal processes have played in actually concentrating the ores (not merely in redistributing the metals locally and modifying their mineralogy).

Our ignorance of partition functions is due to the trace quantities (parts per billion level) in which PGE occur in silicates, coupled with their tendency to concentrate in sulfides or as discrete Pt-group minerals (PGM). This means that mineral separates are highly unreliable because of contamination and that the microprobe is not sensitive enough to analyze for PGE; the problem hinders both field and experimental studies. Radioactive tracer techniques or use of the ion probe (once its resolution becomes improved) should assist with this problem.

In addition to studies pertaining to sulfide saturation, as discussed with reference to Ni- and Cu-rich ores, profitable research will therefore include the following:

- Experimental study of the partitioning of PGE between silicate melts, silicates, and sulfides.

- Careful study of natural occurrences in the light of such experimental data to gain understanding of why PGE are so concentrated in certain sulfide-bearing layers (and not found in others).

OXIDE ORES

OVERALL MODE OF FORMATION

With the exception of TiO_2 -rich ores associated with anorthosites and related rocks, most of these ores are thought to crystallize directly from fractionating mafic (or in some cases possibly ultramafic) magmas. Some differences of opinion exist as to how chromite (in the case of Cr) or magnetite (in the case of V and Ti) has become concentrated. The anorthosite-related, TiO_2 ores are thought to result from the formation of an Fe oxide-rich liquid.

Chromium

Layered Intrusions Chromite occurs in seams, a few centimeters to several meters thick, at specific stratigraphic horizons in the lower portions of intrusions and commonly shows extreme lateral continuity (many tens of kilometers). Examples include the Bushveld complex; the ores of Selukwe, Rhodesia; and the substantial, but currently uneconomical, deposits of the Stillwater complex. The chromite grains are regarded as cumulus, but the mechanism for concentrating them into essentially monomineralic seams remains unclear. Suggestions include the following:

- That chromite crystallization is induced by a sudden increase in fO_2 in the magma because of explosive release of pressure and escape of hydrogen. However, it is difficult to explain how a "sudden" release of hydrogen can occur in a large body of magma.

- That the composition of the crystallizing magma suddenly changed because of assimilation of felsic material or by mixing with an influx of new magma from the original source. It has been shown (Irvine, 1975, 1976) that the composition of the magma can be modified to such an extent by these processes that it will crystallize chromite alone. Although chemically feasible, this model can be criticized on the grounds that it cannot account for the extreme stratigraphic continuity of the chromite seams. Nevertheless, there are many stratigraphically continuous horizons within large layered intrusions (e.g., tops of cyclic units) that appear to require the mixing of old magma with fresh, less-fractionated magma.

- That sudden release of total pressure has affected phase boundaries, moving the magma into the chromite field. This can explain many field relations (Cameron, 1978), but it has yet to be demonstrated experimentally that geologically reasonable pressure changes can shift phase boundaries to the required extent.

Alpine Ultramafic Bodies (Ophiolites) Substantial chromite production from deposits of this type comes from Turkey, the southern Urals, and the Philippines. Because of high-Cr and low-Fe content relative to ores from layered intrusions, ore from these deposits is metallurgically desirable for many uses. Chromite deposits in alpine bodies are characterized by their podiform shape and small size, although pods tend to occur in clusters in a given area. Chromite grains often show magmatic textures in association with intercumulus olivine and commonly cluster together to form nodules up to a few centimeters in diameter. The chromite pods are typically associated with metamorphic-textured harzburgite (interpreted as residual mantle peridotite resulting from the removal of basaltic partial melts) or with cumulus dunite. In the case of the harzburgite association, the chromite has been interpreted as being deposited as cumulus layers within pockets of magma crystallizing in the harzburgite. Because of their high density, these layers of chromite then sink out of the magma pockets into the surrounding residual peridotite as podiform autoliths. Chromite in the cumulus dunites is stratiform and may represent boudinaged remnants of original layering, which, in some cases

has been infolded with harzburgite (e.g., Troodos Complex, Cyprus—Greenbaum, 1977).

Johan and LeBel (1978) present a distinctly different interpretation. They have shown that massive chromite from some ophiolitic complexes in Saudi Arabia and New Caledonia is not only chemically distinct from disseminated chromite in enclosing dunite and harzburgite but also is uniquely characterized by inclusions of unusually forsteritic olivine, chrome-diopside, and pargasitic amphibole and by abundant, saline, fluid inclusions. They suggest that (a) Cr was transported in metallic complexes to the upper parts of chambers accumulating dunite and harzburgite; (b) chromite precipitated on breakdown of the complexes, trapping fluid and other unique solids; and (c) chromite accumulated in irregular layers or pods on the floor.

Vanadium, Titanium, and Iron

Seams in Layered Intrusions Important concentrations of V occur in seams of titaniferous magnetite in the upper zone of Fe-rich gabbro and diorites in the Bushveld complex. The seams range from a few centimeters to 10 m in thickness and are clearly igneous cumulates; however, problems—similar to those discussed with respect to chromite—occur as to the explanation for the concentration of magnetite.

The lowermost seams contain the highest levels of V (2.5 wt. %), with decreasing concentrations of V in progressively higher seams of magnetite. This is a result of the extreme partitioning of V into magnetite, resulting in a rapid V depletion in the magma. The same decrease in V in cumulus magnetite is observed in almost all layered intrusions. TiO_2 also partitions into magnetite and is present in ores in concentrations of 12 to 16 wt. %. The partitioning of Ti appears to be less extreme than that of V, and Ti/V increases in successively higher seams.

Discoidal, generally conformable lenses of magnetite and ilmenite-rich material in the Duluth complex, have compositions that vary in a nonsystematic manner, and, in addition, compositions of the oxide minerals within the lenses are unrelated to those in the surrounding, less intensely mineralized troctolites. These observations led Lister (1966) to suggest that the magnetite-ilmenite lenses are the result of the formation of an oxide-rich, interstitial fluid during crystallization of the cumulate pile and that this liquid was concentrated, perhaps as a result of filter pressing. These deposits, although unimportant economically, suggest that crystallization and settling of oxides as cumulates from a fractionating igneous magma may not be the only method of forming oxide concentrations of apparent strata-bound nature.

Pipelike Bodies in Layered Intrusions Massive pipelike bodies of magnetite, mined for their V content and associated with pegmatitic gabbro, cross-cut igneous layering in the Bushveld complex. The pipes are regarded as the result of crystallization of late-stage, oxide-rich, intracrystalline fluid, filter pressed out of the cumulate pile.

Titanium Associated with Anorthosites Titanium occurs as ilmenite, hemo-ilmenite, titanomagnetite, and rutile (in some cases with varying amounts of apatite) in association with an-

orthosites or gabbroic anorthosites of anorthosite massifs. The ore minerals can occur in irregular massive zones within the anorthosite, as high-grade disseminations in the host rocks, or as massive dikes either cutting the anorthosite or projecting several thousands of meters into adjacent country rocks.

The absence of hydrothermal alteration, the presence of sharp, clearly defined contacts with the enclosing rocks, the presence of exsolution textures indicative of high temperature, the massive nature of many of the deposits, and the cross-cutting relationships that many of the ores show relative to their host rocks have led to wide acceptance of the hypothesis that the ores formed from a dense, immiscible, Fe oxide-rich liquid, near the end stage of crystallization of the anorthosite magmas. It has been suggested that liquid has settled or otherwise migrated through the cumulate pile to form deposits exhibiting the varied forms described above. Preliminary experimental studies (Philpotts, 1967) have shown that a liquid consisting of one third apatite and two thirds magnetite will segregate from a silicate melt if the latter becomes sufficiently enriched in FeO. Experimental liquidus temperatures for this liquid are above 1400°C, although Philpotts (1967) postulates that the presence of volatiles, particularly F and Cl, might lower temperatures to the 1100–1200°C range that would be required for the oxide-rich liquids to coexist with fractionating anorthositic magmas. A problem with this suggestion is that apatite is not associated with the ore in many of these deposits (Table 4.1).

Another suggestion for the genesis of these ores has been that they represent a late-stage fluid formed as the end product of crystallization of anorthosite magma. However, in many anorthosite massifs the normal process of fractional crystallization has been shown to give rise to rocks with Fe-rich pyroxenes and not to a silica-poor, Fe-rich fluid with a composition similar to that of the ores.

Interstitial fluids, trapped within large accumulations of plagioclase, may also possibly fractionate to give an Fe-rich residuum, as was discussed above with respect to the Bushveld vanadiferous–magnetite pipes and the Ti-rich lenses within the Duluth complex. However, the reason for these interstitial fluids differentiating in a different manner to the main portions of the anorthosite intrusions has not been addressed.

USE OF GENETIC MODELS IN EXPLORATION

Figure 4.4 shows the stratigraphic positions of significant concentration of oxide ores in the Bushveld, Great Dyke, and Stillwater igneous complexes and provides an indication of the composition of the oxide minerals (chromite or magnetite) at selected intervals. Important guides to those areas of intrusions that should be prospected for chromite and magnetite can be obtained by study of (1) the petrology of the intrusion; (2) its stratigraphy; (3) the composition of the major minerals—olivine, pyroxene, and plagioclase; (4) the composition of accessory minerals such as chromite and magnetite (although these may be variable at a given level in an intrusion depending on the ratio of oxide to silicate minerals in any given sample); and (5) the stratigraphic level where key accessory minerals first appear as cumulus rather than intercumulus grains.

With respect to chromite deposits associated with alpine ultramafic bodies, recognition of where the particular rocks in question fit into the overall ophiolite succession is important. Most ores occur close to the contact between the (stratigraphically) lower metamorphic-textured harzburgite and overlying, cumulus-textured dunite. In well-preserved ophiolite complexes this may not present major problems, but in ophiolites that have been highly deformed during emplacement into the crust, careful petrographic study, coupled with structural observation on the microscale and macroscale, may be helpful. Fluid-inclusion studies should be undertaken for chromite in podiform deposits, with careful chemical study of the chromite and associated minerals.

OPPORTUNITIES FOR PRODUCTIVE RESEARCH

Despite the many years that have been devoted to the study of layered intrusions, there is still a substantial lack of understanding about the nucleation and growth of crystals in layered intrusions and about the mechanisms and importance of crystal settling. Recent work suggests that classic, gravitational settling models are not adequate to explain the almost monomineralic, “accumulate” zones of rock of which extreme examples account for the economically interesting seams of chromite and magnetite. A complete understanding of crystallization in layered intrusions requires detailed modeling of physical and chemical parameters, including temperature, pressure, viscosity, yield strength of magmas, yield strength of crystals, density of crystals and liquid, and nucleation energies. Once models for the crystallization of intrusions of varying sizes and shapes have been developed, we will be in a much stronger position to predict where important ore seams are likely to form.

The association of ilmenite ores with anorthosites has long been used in empirical exploration. If the concept of late-stage, oxide-liquid immiscibility is correct, it is necessary to explain why this phenomenon appears to be so common in anorthosite complexes and much less common in other layered intrusions. Philpotts (1967) suggests that the higher Na content of anorthositic, as compared with tholeiitic, magmas favors liquid immiscibility, but more work is required to demonstrate this and to distinguish limiting compositions for the Na content of plagioclase, beyond which immiscibility is unlikely to occur. This could prove to be an important exploration tool. Another area worthy of investigation is to see whether the segregation of an Fe-rich fluid interrupts the normal trend of Fe enrichment in a magma, as observed in pyroxenes; if so, studies of the fractional crystallization of an anorthosite complex as recorded by the Fe/Mg ratio of its mafic minerals might serve as a guide as to whether concentrations of V- and Ti-bearing Fe oxides are likely to be present. The major objection to the immiscibility hypothesis rests with the high melting temperatures suggested by experimental work for the Fe₃O₄-rich liquid. Philpotts (1967) has attempted to surmount this in part by suggesting that apatite plays a major role, but liquid immiscibility appears to have been important in deposits that contain little or no apatite. Further careful work on relevant systems, including examination of the fluxing effect of volatiles, is required to substantiate the hypothesis.

MINERALIZATION IN CARBONATITE AND ALKALIC ROCK COMPLEXES

Carbonatite and alkalic rock associations are truly complex in their mineral proportions and suite of rare element concentrations. These factors, plus their highly anomalous magnetic response, have led to prospecting for them out of all proportion to their economic or areal significance. High rare element concentration in residual liquids and abundance of volatile species have led to complexities through gaseous transfer and to overprinting of many original, magmatic features. Strong fractional crystallization, hybridism (assimilation and magma mixing), and strong segregation of immiscible liquids because of the highly fluid nature of the silica-poor liquids make difficult the classification of their contained metallic element concentrations (Agard, 1956; Heinrich, 1966). These rocks are natural fertilizers because of high lime, K, and phosphate contents and are highly susceptible to weathering; thus, eluvial, alluvial, and supergene-enriched deposits commonly grade into fresh orthomagmatic concentrations, further complicating genetic interpretations.

SPECIFIC ASSOCIATIONS

Alkalic rocks of volcanic character are not noted for their economic potential, but their plutonic equivalents—subvolcanic intrusions, breccias, and diatremes—are hosts to interesting concentrations of metals. The classical subdivision of alkalic rocks into agpaite (peralkaline; Ca, CO₂-enriched) is not always easy to make and will not be further considered except to point out that most existing mines are in miassic rocks, more specifically in late, commonly dolomitic and ankeritic varieties of carbonatite. For example, Nb is mined in Niobec's underground operation near Chicoutimi, Quebec, from late-stage Mg- and Fe-bearing carbonatites (Gagnon and Gendron, 1977). Other Nb deposits in tropical and subtropical climates such as that of Araxa, Brazil, are not strictly orthomagmatic, in that eluvial material of original magmatic concentration is mined. Similarly, rare earth elements, the other metal association virtually synonymous with carbonatite, are mined from late-stage carbonatite at Mountain Pass, California (Olson *et al.*, 1954).

Radioactive concentrations of U and Th are common in alkalic complexes and will certainly be of more significance in the near future. Large-volume, low-grade U mineralization in late-stage nepheline syenites and intruded country rocks is well documented at the Ilimaussaq intrusion, Greenland (Sorenson *et al.*, 1974).

The concept is readily formed that elemental concentrations of these important elements are only generated in late-stage fluids (gaseous or magmatic) by strong differentiation of magma. However, it is important that one recognize that this does not imply a unique model for metal concentration in alkalic rock and carbonatite complexes; the following section reveals that many differing aspects of magmatic fractionation have been called on to explain metallic concentrations of economic or subeconomic significance.

ROCK ASSOCIATIONS, METALLIC CONCENTRATIONS, AND DIFFERENTIATION MECHANISMS

The variety of alkalic rock types and elements concentrated within them is not only related to many possible and highly effective fractionation processes but also to a variety of original liquid compositions. This variety stems from smaller amounts of partial melting within the mantle that have probably taken place at greater depths than melting that has produced more voluminous magma types, depths at which depletion in so-called incompatible elements may not have occurred. Partial melting products can be rather siliceous (gabbro-syenite-quartz syenite association) or quite silica-deficient (ijolite-carbonatite association). Intermediate associations are also common (e.g., gabbro-nepheline syenite; ijolite-nepheline syenite) and in any one complex, pairs of these associations may coexist.

Silicate-Carbonate Liquid Immiscibility and Nb, REE Deposits

Many hypotheses have been offered for the coexistence of carbonate-rich and silicate-rich magmas, but an important one appears to be liquid immiscibility. Evolution of separate magmas with fractionation of elements into one or the other may be an important metal concentrating process, accounting for Nb concentrations in carbonatites whether they are in calcite-rich, carbonatite-ijolite associations (e.g., the former Oka mine of St. Lawrence Columbium and Metals Ltd.) or in dolomitic carbonatite (e.g., Niobec's operating mine at St. Honore). At Oka much of the ore occurred in siliceous carbonate rocks, generally interpreted to be stable at high temperatures, that is, with the assemblages diopside-calcite and olivine-calcite. Dolomitic assemblages (often quartz-bearing), are probably low-temperature derivatives of higher-temperature magmas. On the whole, the low-temperature assemblages, often found with hematite, barite, fluorite, and other relatively oxidized phases, are more favorable for prospecting than the high-temperature assemblages in that they represent a later stage and are more likely to be the repositories of "incompatible" elements such as U, Th, and rare earths.

The remarkable concentration of rare earths in late-stage carbonatite at Mountain Pass (Olson *et al.*, 1954) is contained in bastnaesite associated with predominant calcite, barite, and quartz. Other rare earth minerals exist, as do a wide variety of sulfides, sulfates, carbonates, and other minerals. Shearing, brecciation, and associated alteration are widespread and grade into carbonatite dikes and veins. This deposit is noticeably low in Nb, as is the other major, "unique" ore body in carbonatite at Palabora, Transvaal.

Apatite, Magnetite, Ilmenite, and Immiscibility

Assemblages of apatite, magnetite, and ilmenite, often gradational to pyroxenites (jacupirangites) occur with ijolitic, carbonatitic, gabbroic, and, especially, syenitic rocks. Examples of mines of this type are Kiruna, Sweden, and Kovdor, U.S.S.R. (Semenov, 1974). Some of these deposits are layered, not unlike

the association in anorthosites, whereas others are podiform or cross-cutting. Igneous textures and, commonly, the lack of adjacent alteration are suggestive that liquid immiscibility has been important in their genesis as discussed above. Their potential as Fe ore is often limited by high Ti, Mn, and Mg contents, but the combination of recoverable phosphate and Fe as well as significant Nb and rare earth concentrations makes these deposits attractive exploration targets (Parsons, 1961).

Magmatic-Hydrothermal Deposits

The staff at the Palabora Mining Company (1976) concluded that Cu mineralization at Palabora stemmed from solutions permeating the carbonatite-phoscorite pipe along fractures that cut a late, transgressive carbonatite core and its associated carbonatite veinlets. The ore body is zoned from chalcopyrite outward to bornite in the phoscorite. Cubanite is intergrown with chalcopyrite and pyrrhotite in the core, whereas chalcocite is rare and associated with bornite. Valleriite is a common late-stage alteration mineral. The mine produces by-product magnetite, baddeleyite, and uranotorite, as well as phosphate and vermiculite.

Radioactive veins are common in and around alkalic complexes. These are dominantly Th-rich, such as at Iron Hill (Temple and Grogan, 1965), but U-bearing minerals are known. During the magmatic stage, U and Th are enriched in rare earth-rich minerals, but if a gaseous phase evolves, U is probably strongly fractionated into it and is ultimately deposited in veins. This is apparently significant in Fl-rich magmas, where U is complexed with Fl and precipitates when the complex breaks down, as on reaction with Ca-rich rocks (marble, carbonatite, or other such calcemic rock within or outside of the complex). Thus, many radioactive veins associated with alkalic rocks in marble have associated fluorite (Bohse *et al.*, 1974).

Early Cumulates in Ijolite-Carbonatite Complexes

Many apatite-rich rocks, such as the phoscorites from Palabora and Khibina as described by Semenov (1974), are considered to be cumulates from members of the ijolite-carbonatite suite. These commonly contain other heavy, refractory minerals such as baddeleyite, ilmenomagnetite, olivine, pyroxene, and perovskite. At Prairie Lake, Ontario, betafite containing about 20–25 wt. % UO_2 occurs in apatite-pyroxenites (Watkinson, 1978). Similar radioactive pyroxenite cumulates are known from Iron Hill (Temple and Grogan, 1965).

APPLICATIONS TO EXPLORATION AND SUGGESTED AREAS OF RESEARCH

Searches for new deposits, especially of radioactive and rare earth minerals, should be directed toward complexes that exhibit strong differentiation and specifically toward isolating areas rich in dolomitic-ankeritic rocks and barite-fluorite assemblages. These are generally interpreted to be “late-stage” and thus may host significant concentrations of the pertinent “incompatible elements.” The calcitic carbonatites have less potential because of the greater opportunity for potential ore

metals to substitute in early, higher-temperature crystallates. The processes giving rise to early calcitic and late dolomitic assemblages must be better understood, perhaps through detailed petrographic recognition of equilibrium assemblages and interpretations of temperatures, pressures, and fluid-phase compositions analogous to those worked out for the metamorphism of siliceous carbonate rocks. Experimental and theoretical data are available on analogous decarbonation-dehydration reactions (Skippen, 1974). The calcite-dolomite geothermometer should be further tested in this context.

The relative roles of magmatic processes and late-stage gaseous activity are especially ill-defined in late stages of alkalic rock differentiation, in spite of extensive experimental, fluid inclusion, and isotopic studies. Part of the problem results from deuteric overprinting (autofenitization) of early magmatic features that can only be recognized by detailed mapping and petrography. Where mineralization is clearly related to one of these processes, intensive study is called for. A particularly important example is that of the copper ores at Palabora; we need to know whether this complex is truly unique or whether study will reveal clues to other such carbonatite bodies with coincident Cu and S concentrations.

Only when criteria exist for recognition of the effects of magmatic versus late-stage gaseous processes can we hope to be able to understand the accumulating data on fractionation of elements. This is especially true for fractionation of rare earths and U-Th. Resolution will be enhanced by studies of contact rocks of highly differentiated plutons, especially adjacent to “agpaitic” portions, where U deposits are strong possibilities. These may occur as disseminations, pegmatites, or veins; the latter are more probable where country rocks are drastically different in chemistry and thus where fluid-rock interaction is most likely. Intrusions into mafic rocks, limestones, or even early carbonatites are most promising.

The serious problems of beneficiation and extractive metallurgy of refractory minerals such as pyrochlore and other Nb, Ti, and Zr phases require research based on an improved understanding of the mineral chemistry.

Because of the possibility that some sedimentary deposits such as phosphates and barite are expressions of subaqueous alkalic volcanism, geochemical comparisons, photointerpretation of satellite imagery, and paleogeographic reconstruction should be vigorously pursued with the goal of testing this linkage and finding hidden alkalic centers. The relationship of alkalic centers to major tectonic elements and the strong magnetic response to the complexes are useful features in this work.

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Late Magmatic and Hydrothermal Processes in Ore Formation

C. WAYNE BURNHAM *and* HIROSHI OHMOTO
The Pennsylvania State University

INTRODUCTION

Probably most of the geologic and physical-chemical factors of major importance in magmatic-hydrothermal ore-forming processes are recognized. Few, however, are sufficiently well understood to be properly integrated into sound conceptual genetic models that constitute the basic framework for understanding the exceedingly complex interactions of these numerous factors in processes of ore formation. The relatively high level of understanding of ore formation in porphyry copper-molybdenum deposits, for example, is largely responsible for a correspondingly modest level of success in recent discoveries of new deposits, yet millions of dollars continue to be spent annually in fruitless search for economic mineralization in areas where present conceptual models indicate the existence of favorable targets for exploration. Thus, despite this relatively high level of understanding, it apparently is not yet adequate to yield reliable guides to ore.

The geologic and mineralogical features that are common to virtually all porphyry copper deposits have been appropriately characterized by Gustafson and Hunt (1975) as a basic theme, a theme that is developed through orchestration of numerous

processes whose operation is essential to the formation of each deposit. They also regarded the differences in geological and mineralogical features, from one deposit to another, as variations on the basic theme, variations that may reflect operation of additional processes or differing intensities of basic-theme processes. Whether these variations are caused by one or the other of these factors, they may or may not be critical to the formation of ore in a given deposit.

The processes that constitute both the basic theme and the variations on this theme, whether in a porphyry copper or other magmatic-hydrothermal system, naturally fall into three groups according to the environmental factors that dominate their control. The first group includes those processes that traditionally have been referred to as *orthomagmatic processes*; it is enlarged here to include some highly important processes by which hydrous, metal-bearing magmas are generated from different kinds of source rocks in different tectonic regimes, as well as the more commonly considered processes of magma emplacement and solidification. These orthomagmatic processes and the factors that control them have been historically more the province of igneous petrologists than of students of ore deposits. Thus, although many of the processes are moderately well

understood in terms of their roles in the formation of igneous rocks, they have not generally been given adequate consideration in the construction of genetic models for the formation of associated hydrothermal ore deposits.

At the other end of the process continuum lies a group of strictly *hydrothermal processes* whose only direct connection with magmas may be in the source of thermal energy that drives them. Much has been learned about these processes, especially in the last 10 years, but much more must be learned before our understanding is adequate to guide exploration effectively for the ore deposits they produce. Difficulties in understanding this group of processes arise from the large number, and extreme variability, of the environmental factors that affect them.

In the middle ground between the hydrothermal and the orthomagmatic processes lies an ill-defined and poorly understood group of *transitional processes* that are not readily distinguishable from orthomagmatic processes at high temperatures and generally higher pressures and from strictly hydrothermal processes at lower temperatures and generally lower pressures. For present purposes, the upper limit of transitional processes may be arbitrarily set at the stage where the operation of orthomagmatic processes leads to formation of a separate magmatic aqueous phase, and the lower limit may be even more arbitrarily set at the H_2O -saturated solidus of the magma, i.e., the temperature, for a given total pressure, below which hydrous silicate melt is not thermodynamically stable. It must be realized, however, that kinetic factors play an important role in these dynamic systems, and quasi-orthomagmatic conditions may extend well into the subsolidus region in some cases.

In the formation of the various types of hydrothermal ore deposits the relative importance of orthomagmatic processes generally diminishes with an increasing importance of hydrothermal processes in the order listed in Table 5.1. Transitional processes, either through their chemical effects or their physical-mechanical effects on wallrocks, play a primary role in the formation of many deposits of nearly every type, but their role may be secondary or minor in others, especially in the formation of certain "replacement and vein" deposits.

TYPES AND IMPORTANCE OF LATE MAGMATIC AND HYDROTHERMAL ORE DEPOSITS

The important types of ore deposits formed by the above three groups of processes and the commodities recovered from each type are summarized in Table 5.1. Except for magnesium, chromium, and platinum, which have not been recovered in significant quantities from deposits of these types, the list includes virtually all of the metals that are vital to our civilization.

MAGMATIC-HYDROTHERMAL DEPOSITS

The four major types of magmatic-hydrothermal deposits are (1) carbonatites (discussed in Chapter 4), (2) pegmatites, (3) "porphyry" types, and (4) contact metasomatic types ("skarns"). The ore deposits in this group generally occur within, or im-

mediately adjacent to, intrusive bodies of igneous rock, to which they are commonly regarded as being genetically related. Interpretation of the ores also yields evidence of their having been formed at temperatures in the range of 350–750°C and at depths commonly greater than 1 or 2 km.

Economically, carbonatite deposits are the major source of Nb and the rare earth elements, as well as a moderately important source of Ta and Th. Pegmatite deposits constitute the major source of Ta, Be, Sc, and the rare alkali metals (Li, Cs, Rb), as well as of mica, feldspars, and gem minerals (such as beryl, tourmaline, and topaz); they also are a moderately important source of Nb, Zr, and rare earth elements.

"Porphyry"-type deposits, of which three subtypes are recognized, are economically the most important types of magmatic-hydrothermal ore deposits. The Cu-Au subtype, generally associated with stocklike bodies of porphyritic diorite, granodiorite, or quartz monzonite, is the major source of Cu, Ag, Se, and Te and an important source of Mo, Au, and Bi. As the associated igneous rocks become more granitic in composition, the Cu-Au subtype gives way to a Mo subtype, the major source of Mo and Re and an important source of W. The Tin subtype deposits generally are associated with alkali-rich granite porphyries and constitute the major source of Sn.

Contact metasomatic-type ("skarn") deposits also may be subdivided into three subtypes on the basis of major metal associations. The Fe-Cu-Co subtype generally is associated with dioritic to gabbroic intrusions into carbonate rocks and is a moderately important source of Fe, Cu, and Co. Intrusions of intermediate to felsic igneous rocks into carbonates give rise to the Cu-Zn-Pb-Ag subtype, which is a significant source of Mo, Cu, Zn, Ag, and Cd. The W subtype is associated with intrusions of felsic magmas into carbonate rocks and is the major source of W.

OTHER HYDROTHERMAL DEPOSITS ASSOCIATED WITH IGNEOUS ACTIVITY

The three main types of deposits in this group are (1) replacement and major vein types, (2) submarine geothermal type, and (3) subaerial geothermal type. Except possibly for Th-rare earth-type vein deposits, ores in this group appear to have been formed at generally lower temperatures (approximately 100–350°C) and shallower depths than the magmatic-hydrothermal group of deposits.

On the basis of characteristic metal associations, replacement and vein type deposits may be divided into the following five subtypes:

1. The Cu-Pb-Zn-Au-Ag subtype, which generally occurs as replacements of carbonate rocks and in major veins near intrusive igneous bodies, is commonly not readily distinguished from the Cu-Zn-Pb-Ag contact metasomatic ("skarn") subtype deposit. Deposits of this subtype are an important source of Sb, Bi, As, Ga, Ge, and In, as well as of Cu, Zn, Au, Pb, Ag, and Cd.

2. The W-quartz vein subtype is a highly important source of W.

TABLE 5.1 Types and Importance of Ore Deposits Formed by Late Magmatic Processes^a

Types of Deposits	Ferrous Metals														Nonferrous Metals														Nuclear Fuels										
	Fe	Ni	Mo	Mn	W	Co	V	Ta	Nb	Al	Cu	Ti	Zn	Au	Pb	Sn	Ag	Be	Cd	Zr	Hg	Sb	Bi	Rb	Se	As	Te	Re	In	Sc	Rare earths	S	F	Mica field-spar	U	Th			
<i>Magmatic hydrothermal deposits</i>																																							
Carbonatites								○	●											X																			
Pegmatites	X			X				●	○				X			X	●			○		X	●																
“Porphyry” types																																							
Cu-Au type	○										●				○		●				○				●		X	●											
Mo (±W) type	●			○													X					X		X		X													
Sn type																●						X		X		X		X											
“Skarn” types																																							
Fe-Cu-Co type	○					○	X				○																												
Cu-Zn-Pb-Ag type		○									○																												
W type					●											X																							
<i>Other hydrothermal deposits</i>																																							
Replacement and vein types																																							
Cu-Pb-Zn-Au-Ag type																																							
W-quartz veins	X																																						
Au-quartz veins																																							
U-Co-Ni-Ag veins																																							
Th-rare earth veins																																							
Submarine geothermal types																																							
Subaerial geothermal types	X																																						

^a Within each group of commodity (e.g., ferrous metals), commodities are arranged from left to right in order of decreasing importance in terms of their dollar values of U.S. demand. Relative importance of deposits is indicated by ●, major (more than 20 percent of the commodity recovered from this type of deposit); ○, moderate (between about 2 and 20 percent of the commodity recovered); X, minor (less than 2 percent of the commodity recovered). Source of Data: Brobst and Pratt (1973) and U.S. Bureau of Mines (1970).

3. The Au-quartz vein subtype is a moderately important source of Au.

4. The U-Co-Ni-Ag vein subtype is a minor source of these metals.

5. The Th-rare earth vein subtype also is a minor source of Zr, rare earth elements, and Th.

The most important deposits of the submarine geothermal type occur as stratabound massive sulfide ores associated with submarine volcanogenic rocks. They are a major source of Zn, Pb, and Cd and an important source of Cu, Au, Ag, and As. Ores of the subaerial geothermal-type deposits, on the other hand, occur typically as disseminations or minor veins in various types of rock; they are the major source of Hg and a moderately important source of Au, Ag, and Sb.

PRESENT LEVEL OF UNDERSTANDING

ORTHOMAGMATIC PROCESSES

Source Rocks and Magma Generation Processes

Orthomagmatic processes of importance in ore formation commence with the generation of magmas by partial melting of older rocks, whether in mafic oceanic crust of subduction zones or in mafic amphibolites and felsic metasedimentary rocks of the lower continental crust. Because of their relatively high average contents of the base and precious metals, mafic source rocks tend to yield partial melts (magmas) enriched in these elements. On the other hand, felsic metasedimentary rocks tend to yield partial melts that are commonly enriched in Sn, the alkali metals, Be, Ta, Nb, and the rare earths. In both types of source rocks, however, the partial melting process constitutes an important step in the concentration of the ore elements.

Partial melting is induced by the presence of H_2O , and the pressure-temperature regime in which melting occurs depends to a large extent on the form in which H_2O occurs. At the great pressures of the deep continental crust—and even greater pressures in subduction zones—it is probably that most if not all of the H_2O in the source rocks, just prior to the onset of melting, is bound as hydroxyl in hydrous minerals and the rocks have essentially zero porosity. In mafic rocks, such as subducting oceanic crust, the principal hydrous mineral is amphibole, and in felsic metasedimentary rocks the micas predominate. In both rock types, however, the total H_2O content probably is usually less than 2 wt. %, and this places definite constraints on the amount of melt that can be produced at a given depth (pressure) and temperature.

At depths shallower than about 75 km, a nonporous mafic amphibolite begins to melt at about 1000°C and the H_2O content of the melt must exceed about 3.0 wt. % (Burnham, 1979). On the order of 20 percent melt can be produced for each percent of H_2O in the original rock. At depths greater than about 75 km, as in a subduction zone, amphibole is not stable at any temperature; hence, melting of mafic amphibolite can begin at temperatures as low as 700°C. For melting to occur at such low temperatures, however, the initial melt must con-

tain 25 wt. % H_2O or more; therefore, the amount of melt produced is generally less than 4 percent for each percent of H_2O in the amphibolite. Nonporous muscovite mica-bearing metasedimentary rocks also begin to melt at temperatures near 700°C under pressures of the lower continental crust. In this case, however, the first-formed melt must contain in excess of about 9 wt. % H_2O ; hence, only about 10 percent melt is formed for each percent of H_2O in the original rock.

The melting relationships outlined above serve to illustrate three features of magma generation in the lower continental crust and in subduction zones that are of utmost importance in ore genesis. (1) Partial melting of amphibole- or mica-bearing rocks at high pressures, even in the absence of pore fluid, produces initial melts in which the H_2O content always exceeds about 3 wt. %, regardless of the total amount of H_2O bound in hydrous minerals. (2) These melts range in composition from granitic to dioritic, as do the igneous rocks that are characteristically associated with magmatic-hydrothermal ore deposits. (3) The amount of initial melt formed is directly proportional to the H_2O content of the original rock. A geologically reasonable H_2O content in the source of 1.0 wt. % typically produces 10–25 percent melt.

The first feature, a minimum of about 3.0 wt. % H_2O in the initial melts, is important for the following reasons: (1) it assures that the magmas produced, when emplaced in the shallow crustal environments required for hydrothermal ore-forming processes to operate, will evolve a separate magmatic aqueous phase upon cooling and crystallization; (2) it enhances the solubilities of metal sulfides in the initial melts by perhaps an order of magnitude over those in anhydrous melts of the same silicate composition, through equilibrium reactions such as $2FeS(\text{solid}) + 2H_2O(\text{melt}) + SiO_2(\text{melt}) = Fe_2SiO_4(\text{melt}) + 2H_2S(\text{melt})$, and thereby provides the hydrous magmas with high sulfur-carrying capacity; and (3) it generally leads to the crystallization of hornblende and/or biotite from the magmas upon cooling at depths greater than about 2 km, thus providing an exploration guide to those intrusive igneous bodies that might have been associated with hydrothermal ore-forming processes.

The second feature, the dioritic to granitic compositions of the hydrous magmas formed, is important because most ore deposits of the magmatic-hydrothermal type are associated with intrusive igneous bodies of these compositions. Thus, hydrothermal activity is closely associated with these compositional types of igneous rocks because hydrous minerals in the source rocks, whether micas in felsic metasedimentary rocks or amphiboles in mafic amphibolites, play a major role in the generation of hydrous magmas of intermediate to felsic composition.

The direct dependence of the amount of melt formed on the total H_2O content of a given source rock provides a mechanism for greatly enriching early formed partial melts with certain trace elements, relative to their concentrations in the source rocks. For those elements that are contained in minor mineral phases of the source rocks, which dissolve completely in the early formed melts, enrichment factors are inversely proportional to the H_2O content of the source rock. On the other hand, for those elements that are contained in major mineral solid solutions that coexist with early formed melts, enrichment

factors are dependent on partition coefficients among the co-existing phases. An element such as Cu, which is concentrated in the minor Fe-rich sulfides of mafic amphibolites, for example, may undergo a fivefold or greater enrichment in early formed melts; however, an element such as Pb, which substitutes for K in alkali feldspars, may undergo little enrichment in melts formed from metasedimentary rocks. For those elements that undergo marked enrichment in early formed melts, hydrous magma generation by partial melting constitutes a critical initial process in the multiplicity of processes that ultimately lead to ore formation.

Magma Emplacement

The intrusive igneous bodies associated with magmatic-hydrothermal base and precious metal deposits appear to have been emplaced at depths generally less than 10 km; many of them reached depths as shallow as 1 or 2 km, and some of them probably vented at the surface to produce compositionally equivalent extrusive rocks. They can thus be appropriately regarded as parts of subvolcanic systems and, as such, tend to have been emplaced passively in extensional tectonic regimes. Zones of structural weakness in the basement rocks, therefore, have commonly exerted considerable influence on the localization of these bodies and the volcanic centers with which they are commonly associated.

In contrast to this near-surface environment, where most wallrocks quasi-elastically yield to intrusive (telluric) pressures to produce steeply dipping fractures, ore-bearing granite pegmatite bodies have been emplaced at depths generally greater than about 6 km, where plastic deformation of the wallrocks is more prevalent. Pegmatite bodies therefore tend to be localized by pre-existing local structural weaknesses in the host rocks, whether produced by foliation surfaces, old fractures, or a combination of the two.

Magmatic differentiation by gravitational settling of early formed crystals appears generally to have played a relatively minor role in concentrating volatiles and metals in the upper parts of those magma bodies with which hydrothermal activity is associated. Differentiation during flow of a crystal-charged magma or by squeezing out ("filter pressing") of interstitial melt, on the other hand, appears to have played an especially important role in the formation of some ore bodies in pegmatite. The role of convection, either natural or forced by crystal settling near the walls, also appears to have been minor in effecting upward concentration of volatiles and metals in magma bodies with which hydrothermal ore deposits are associated.

Hydrous magmas of intermediate composition generally are out of chemical equilibrium with more silicic and potassic wallrocks through which they may pass or in which they may be emplaced. There is thus a tendency for the marginal parts of these magmas to assimilate this type of wallrock reactively, causing the melt fraction to become enriched in SiO₂, K, and other elements with which the melt is undersaturated. The process of assimilation, therefore, might be an important factor in the development of some ore-forming systems, such as with the Sn-bearing porphyries of South America.

Crystallization of Hydrous Magmas

Although the nature of the source rocks and the processes of hydrous magma generation and emplacement are critically important to ore formation in magmatic-hydrothermal systems, certain processes must operate during crystallization of a magma to further concentrate the ore elements into minable deposits. Among these numerous processes, the most critical one is the evolution of a separate, H₂O-rich (aqueous) volatile phase. Were it not for this process, pegmatite ores would not form (Jahn and Burnham, 1969), the fracture systems of porphyry Cu-Mo and other stockwork deposits would not develop, contact metasomatic processes would not operate, and many of the ore-localizing structures produced by explosive volcanism would not exist.

The evolution of an aqueous phase from a given magma is controlled principally by the solubility of H₂O in the melt, which is strongly pressure dependent but only weakly temperature dependent. For example, at a pressure of 500 bars (5×10^7 Pa), which is equivalent to a depth of about 2 km, the maximum solubility of H₂O in melts of dioritic to granitic composition is only about 3.0 wt. %, whereas at a pressure of 2000 bars (approximately 8-km depth) it is 6.3 wt. % and at 5000 bars (approximately 18-km depth) it is 10–11 wt. %. Thus, such melts that initially contained 2.0 wt. % H₂O would be water saturated, during cooling, after they have become about 33 percent crystalline at 2 km, 73 percent crystalline at 8 km, and about 83 percent crystalline at 18 km. Further cooling and consequent crystallization beyond these points of saturation causes H₂O to separate from the residual melt by a process commonly called second, or resurgent, boiling. Eventually all the original H₂O content of the magma, except that bound structurally in hydrous minerals (0.5–0.8 wt. %), must be evolved as a separate fluid phase.

During cooling of the magmas in the foregoing examples, plagioclase generally crystallizes early, followed by pyroxene in dioritic magmas and by alkali feldspars or quartz in granitic magmas. Their crystallization enriches the residual melt not only in H₂O but in all other constituents not partitioned in favor of these minerals. This enrichment process by fractional crystallization is thought to be important in the production of ore-bearing granite pegmatite magmas, especially in deep-seated magma bodies, where enrichment factors in the residual melts for elements such as Li and Be may be as high as 10, possibly higher. It also is thought to be important in higher-level intrusive bodies of metal sulfide-bearing magmas, where fractional crystallization concentrates the ore metals, S, and Cl in the more hydrous residual melt.

TRANSITIONAL PROCESSES

In accordance with earlier definitions, the formation of a separate magmatic volatile (aqueous) phase by second, or resurgent, boiling is arbitrarily chosen to distinguish those processes that operate almost entirely within condensed crystal-melt systems (orthomagmatic processes) from those that operate in co-existing condensed-volatile systems, which are here called transitional processes. Chemically, orthomagmatic processes

are controlled primarily by crystal–melt equilibrium, whereas transitional processes are dominated by melt–volatile (aqueous fluid) equilibrium. Also, orthomagmatic physical processes are controlled largely by magma viscosity and density contrasts between crystals and melt, whereas transitional physical processes are dominated by volume changes that accompany the second-boiling reaction.

H_2O -saturated melt \rightarrow crystals + volatile phase.

Physical Processes

A body of hydrous magma emplaced in colder wallrocks, whether it be a shallow-seated porphyry magma or a deeper-seated pegmatite magma, must lose heat to its surroundings, hence crystallization generally proceeds from the walls inward. As a consequence of this fact and the very low diffusivity of dissolved H_2O in silicate melts, the melt in such a body of magma first becomes saturated with H_2O near the margins. The formation of this H_2O -saturated rind or carapace may, under quasi-static conditions, effectively isolate the interior of the body to the transfer of matter (except hydrogen) either in or out. These conditions are regarded as essential to the development of pegmatites (Jahns and Burnham, 1969), as well as of porphyry Cu–Mo systems and of explosive volcanism (Burnham, 1979).

As second boiling proceeds inside this H_2O -saturated rind, the magma body must either expand or the internal pressure must increase, as the reaction H_2O -saturated melt \rightarrow crystals + volatile phase takes place with an increase in volume at all crustal pressures. To a first approximation, this increase in volume is directly proportional to the H_2O content at saturation and inversely proportional to pressure. Thus, a body of H_2O -saturated pegmatite melt at 2000 bars pressure (6.3 wt. % H_2O) will expand about 7 percent upon complete crystallization, whereas the same body saturated with H_2O at 5000 bars (11 wt. % H_2O) will expand less than 2 percent. Perhaps this effect of pressure provides an explanation of why some pegmatite bodies contain considerable void space, in which gem minerals commonly occur, and other bodies are only moderately porous and contain no gem "pockets."

In contrast to these relatively small volume increases, a body of granodioritic melt containing 3.0 wt. % H_2O will expand approximately 50 percent upon complete crystallization at a depth of 2 km (500-bars pressure). Furthermore, this same body, at a depth of 4 km, now 30 percent crystalline at H_2O saturation, will expand more than 15 percent. At these shallow depths, most types of wallrocks have high rigidity and cannot accommodate such large volume changes by plastic deformation. As cooling and crystallization proceed, pressure inside the H_2O -saturated carapace must increase. Theoretically, this excess internal pressure could reach several thousand bars, but the tensile strength of the strongest wallrocks is only a few hundred bars at most. Therefore, brittle failure occurs, and, because the direction of least principal stress lies essentially in the horizontal plane, expansion occurs principally in that direction and the ensuing fractures thus tend to be nearly vertical in orientation. Also, because the roofrocks are mechanically coupled to the underlying H_2O -saturated magma carapace

through viscous interstitial melt, expansion of the magma in the horizontal plane places these roofrocks under tension. Myriads of small fractures therefore propagate upward to produce stockworks and the intensely shattered rocks that are so characteristic of porphyry Cu–Mo deposits.

In essence, the mechanical energy released by second boiling during the inevitable cooling of a shallow-seated hydrous magma is regarded as the major cause of fracturing, which in turn is essential to the localization of ores in most magmatic–hydrothermal ore deposits. The fractures thus produced may be of the stockwork type, the large vein type, or the even larger caldera collapse structures that accompany explosive volcanism. In any case, these fractures serve as high-permeability channelways for the migration of hydrothermal ore-forming fluids, whether the fluids are of magmatic, meteoric, or seawater origin.

Chemical Processes

The generation of a magmatic aqueous phase by second boiling is accompanied by partitioning of all elements in the system such that the chemical potential or fugacity of each chemical species is the same in all phases at equilibrium. The volatile element, Cl, which is dissolved in silicate melts mainly as chloride ion (Cl^-), is partitioned strongly toward the magmatic aqueous phase, because (1) chloride minerals are not stable in magmas of intermediate to felsic composition and (2) it forms highly stable, neutral chloride complexes with hydrogen, alkali metals, alkaline earths, and heavy metals in aqueous solutions at magmatic temperatures and low to moderate pressures. Fluorine also forms stable neutral fluoride complexes in magmatic fluids, but high solubilities of F in silicate melts, coupled with high thermal stabilities of minerals such as fluorite, topaz, and micas, cause F to be partitioned largely toward the condensed phases. S, which is dissolved in hydrous melts principally as bisulfide ion (SH^-), also is partitioned strongly toward the magmatic aqueous phase, unless a sulfide mineral such as pyrrhotite becomes stable. Carbon dioxide, dissolved sparingly in silicic melts as such and very strongly partitioned toward the volatile phase, appears to play only a minor chemical role in transitional processes at the magmatic stage.

Partition coefficients of the above-named volatiles, between melt and aqueous fluid, appear to be relatively insensitive to temperature and, except for S, to pressure. Because S is dissolved in hydrous melts principally as SH^- , but exists in the aqueous phase as both H_2S and SO_2 , its partition coefficient is sensitive to water pressure (fugacity of H_2O , $f_{\text{H}_2\text{O}}$) and to the fugacity of oxygen (f_{O_2}). Under the f_{O_2} of a given phase assemblage, increasing pressure ($f_{\text{H}_2\text{O}}$, hence f_{H_2}) increases the proportion of H_2S to SO_2 in the aqueous phase; hence, the partition coefficient for S (total) is decreased. On the other hand, increasing f_{O_2} at a given pressure, as by diffusive loss of hydrogen from the system, increases the proportion of SO_2 , hence the partition coefficient for total S is increased. These phenomena, which arise because SO_2 is much less soluble than H_2S in hydrous magmas, are of great importance to sulfide ore formation. They provide mechanisms for generating high concentrations of both S and heavy metals (the latter almost entirely as chlorides) in the magmatic aqueous phase, especially

in Cu–Au subtype “porphyry” magma systems that were generated from mafic amphibolites (in the absence of carbonaceous material), where total S contents of 2 or 3 moles per kilogram of H_2O ($f SO_2/f H_2S$ as high as 10) may be produced. Tin subtype “porphyry” magmas, on the other hand, appear to have been generated mainly from carbonaceous metasedimentary rocks; hence, they tend to yield fluids with much lower $f SO_2/f H_2S$ and total sulfur contents.

The molal concentration of Cl in a magmatic aqueous phase is about 40 times that in a coexisting melt (Kilinc and Burnham, 1972). Except for silica, chloride complexes commonly constitute the major portion of the total dissolved solutes. For this reason, the relative proportions of the various major chloride complexes and the manner in which these proportions respond to changing conditions of equilibrium are important factors in understanding such apparently diverse phenomena as mineral zoning in pegmatites and high-temperature hydrothermal alteration patterns in porphyry Cu deposits.

The major aqueous chloride complexes in equilibrium with typical granite melts are NaCl, KCl, and HCl, with NaCl and KCl constituting about 90 percent of the total, and the molal ratio of NaCl to KCl is the same as the molal ratio of Na to K in the melt (Burnham, 1979). However, with the appearance of a mineral such as muscovite, which contains both K and hydrogen, the HCl content decreases markedly, the KCl content decreases, and the NaCl content increases to maintain the chloride stoichiometry. As a consequence, NaCl/KCl in the aqueous phase becomes greater than Na/K in the melt. The relative proportions of the various chloride complexes even in this relatively simple system are complexly dependent on both bulk melt composition and the nature of the coexisting minerals.

In a compositionally more complex system, such as a granodiorite magma, chloride complexes with Ca ($CaCl_2$) and especially Fe ($FeCl_2$ and $FeCl_3$) must be included as major aqueous species ($MgCl_2$ is always a very minor constituent). The addition of these two constituents to the melt–volatile system does not affect the HCl content or the equality between NaCl/KCl and Na/K in the melt, but the sum of NaCl and KCl is reduced by two or more times the molal concentration of Fe and Ca. In fluids coexisting with melt, plagioclase, and magnetite at high pressures, Fe chlorides and $CaCl_2$ are present in subequal amounts and, together, complex about 20 percent of the total chloride. At low pressures (500–1000 bars), on the other hand, only about 5 percent of the chloride is complexed as $CaCl_2$, but in either NaCl or KCl solutions more than 30 percent of the total Cl can be complexed with Fe.

Another important difference between the granite and granodiorite systems is the role of hydrous minerals. In contrast to the granite systems, where precipitation of K-bearing micas causes NaCl/KCl in the aqueous phase to be greater than 1 (irrespective of Na/K in the melt), early crystallization of Na-bearing hornblende in granodioritic magmas causes NaCl/KCl to shift markedly in the opposite direction, toward values much less than 1, even where the ratio of Na to K in the melt is greater than 1. In the presence of both hornblende and boitite, as might be expected, NaCl/KCl is close to unity, irrespective of the corresponding ratio in the melt. Thus, the relative pro-

portions of the major chloride complexes in the magmatic aqueous phase are strongly dependent on melt composition, pressure, and the nature of the coexisting mineral assemblage.

The high ratio of K to Na in aqueous chloride solutions coexisting with hornblende-bearing magmas provides a possible explanation for the extensive K metasomatism (potassic alteration) that is characteristically associated even with K-poor dioritic porphyry Cu bodies. On the other hand, the relatively high concentrations of HCl in the aqueous phase, prior to the appearance of hydrous minerals, may account for the occurrence of topaz in some pegmatites and Sn greisens, as well as the occurrence of andalusite in some porphyry Cu–Mo alteration haloes. Also, the very high concentrations of Fe in the magmatic aqueous phase, especially at low pressures, may account not only for contact metasomatic skarn ores in carbonate wallrocks but also for the overwhelming abundance of pyrite in most porphyry copper ores.

Little is known about the partitioning of most ore metals between magma and aqueous chloride solution. By analogy with Mn and Zn, which are partitioned in favor of the aqueous phase by a factor of about two times the molal concentration of chloride squared (Holland, 1972), it is expected that elements more chalcophile than these two would be partitioned even more strongly toward the aqueous phase. Therefore, aqueous chloride solutions in which the fugacity of SO_2 is approximately that of H_2S should be effective in scrubbing a magma and its immediately superjacent roofrocks of their valuable metal content.

HYDROTHERMAL PROCESSES

With falling temperatures or marked decreases in internal fluid pressures, transitional chemical processes give way to those hydrothermal processes that are dominated by crystal–volatile equilibrium. The boundary between these two regimes, arbitrarily defined as the H_2O -saturated solidus of the magma, may be relatively sharp in some systems and highly gradational in others. The relatively sudden brittle failure of the wallrocks in a porphyry Cu system, for example, may cause part of the system to pass rather abruptly from one regime to the other. In a pegmatite system, on the other hand, both regimes may coexist in different parts of the system and “communicate” with each other through the volatile phase. Indeed, the coexistence of the two intercommunicating regimes apparently is essential to the development of mineralogic zoning in pegmatites and, hence, to the concentration of many pegmatite ores. Also, the largely closed hydrothermal circulation system established at this stage of pegmatite formation is believed to be ultimately responsible for the localization of gem minerals, as well as minerals rich in Sn, Ta, Nb, U, Th, and the rare earths.

The comparatively more rapid passage of the magmatic aqueous phase into the hydrothermal regime of a developing porphyry Cu–Mo fracture system generally leads to conditions of gross disequilibrium between the fluids and cooler wallrocks. The nature of this disequilibrium, however, is dependent on the initial conditions of equilibrium in the magmatic system, as well as on the nature of the wallrocks and the extent to which temperature and pressure decrease. Aqueous chloride solu-

tions from a high-temperature magmatic source, as discussed previously, tend to be rich in HCl; hence, they will react with feldspathic wallrocks to produce aluminum silicate (mainly andalusite or topaz) alteration, with or without biotite, at higher temperatures and muscovitic (sericitic, phyllic) alteration at lower temperatures. Fluids that equilibrated initially with hornblende-bearing magma, on the other hand, are enriched in KCl relative to NaCl and especially HCl; their interaction with noncarbonate wallrocks is largely one of fixing K in feldspar and biotite ("potassic alteration") by exchange with Na and especially Ca. These exchange reactions therefore lower KCl/HCl in the aqueous phase, which in turn leads to entry into the stability field of muscovite ("sericitic" alteration) near its high-temperature limit for the prevailing pressure. Thereafter, further cooling of the fluids causes KCl/HCl to increase, as K-rich feldspar is converted to muscovite and quartz.

The drop in pressure and temperature attending escape of the magmatic aqueous phase into fractured wallrocks may result in condensation of a chloride-rich liquid that consists mainly of NaCl and KCl. Owing to differences in density, this liquid may be segregated from the coexisting volatile phase, which has become enriched in HCl, CO₂, SO₂, and H₂S. This acid-enriched volatile phase may be responsible for part of the sericitic and argillic (clay-rich) alteration in the upper, cooler parts of fracture systems.

Perhaps a more important cause of this lower-temperature "acid" alteration stems from cooling a S- and metal chloride-bearing magmatic aqueous phase in a low-pressure environment. At magmatic temperatures and pressures below about 500 bars, SO₂ hydrolyzes to H₂S and H₂SO₄. The resultant increase in H₂S fugacity causes precipitation of sulfide ore minerals from the metal chloride complexes (mainly of Fe) in aqueous solution, which in turn produces HCl. This HCl production is further enhanced by precipitation of anhydrite (CaSO₄) from the aqueous CaCl₂ produced by the K-Ca exchange reaction described above, as well as by direct reaction between aqueous H₂SO₄ and plagioclase or other Ca-bearing minerals in the wallrocks. Also, within the stability field of muscovite, sericitization of K feldspar releases Ba, which may be precipitated as barite (BaSO₄) at lower temperatures.

In feldspathic wallrocks, the amount of HCl thus produced is controlled by hydrolysis-type reactions with the silicate mineral assemblages that commonly yield muscovite or other aluminous minerals. For a given temperature, pressure, and equilibrium assemblage, the HCl content is directly proportional to total chloride content of the fluid. In carbonate wallrocks, on the other hand, HCl contents of the fluids are fixed at very low levels, irrespective of total chloride contents, by decarbonation reactions that result in replacement of carbonate wallrocks by sulfide ore minerals. These replacement reactions commonly are accompanied or preceded by other carbonate replacement reactions that involve precipitation of Fe-bearing silicates and oxides (mainly magnetite) to form typical skarn ores. These latter reactions neither consume nor produce HCl, but they do increase the activities of Ca and Mg chlorides in the fluid and produce copious amounts of CO₂. The resultant increase in CO₂ fugacity, in turn, tends to inhibit further calc-silicate formation, which may lead to eventual replacement of

carbonate rocks by highly siliceous oxides ("jasperoid") and to secondary dolomitization on reduction in CO₂ fugacity.

Fluids emanating from a chloride-poor magmatic source are correspondingly poor in HCl, S, and Fe and other metals, but they are moderately richer in SiO₂ and much richer in Al₂O₃. As a consequence, their metasomatic interactions with carbonate wallrocks produce mainly calc-silicate mineral assemblages in which aluminum garnet (grossularite) and magnesian pyroxene (diopside) figure more prominently than Fe-rich garnet (andradite) and pyroxene (hedenbergite) that are typically associated with "skarn" ores.

At our present level of understanding, the various processes briefly described in the foregoing pages appear to suffice, in a general way, to explain the formation of pegmatite and "skarn" ores, as well as the basic "theme" of porphyry-type deposits. However, other processes not directly connected with magmatism must operate to produce other types of hydrothermal ore deposits, as well as important variations on the basic "theme." Once fluid pressures in a fracture system connected to a magmatic source approach ambient hydrostatic pressures in the wallrocks, the potential exists for ingress of water from extraneous sources into the hydrothermal system. These waters may be of near-surface meteoric origin in subaerial environments or of seawater origin in submarine volcanic environments.

Meteoric and Seawater Hydrothermal Systems

Emplacement of magmas at depths shallower than 6 or 7 km generally creates large-scale convective circulation systems in the groundwaters of the region. These groundwaters, whether meteoric water or seawater, are heated near the intrusive body and rise. Some of this heated water may escape to the surface in hot springs, but much of it may migrate laterally and descend, on cooling, to return again in the next cycle. In the simplest case, the circulation system thus established would be toroidal and centered on the apical parts of the intrusive body, where the country rocks tend to be more extensively fractured and, hence, to have greater bulk permeability.

In detail, however, the physical characteristics of such circulation systems are affected by various geologic and hydrologic factors, such as (1) the size, depth, and shape of the heat source (igneous body); (2) the location, orientation, and nature of major faults and boundaries between different rock units; and (3) variations in bulk porosity and permeability of the country rocks, both with time and with location in the system. Some relatively large intrusive igneous bodies apparently create high-temperature (100–400°C) hydrothermal circulation systems that extend several tens of kilometers from the discharge areas to the recharge areas and to depths of several kilometers. Smaller intrusive bodies tend to create correspondingly smaller circulation systems.

In regions where explosive volcanism has greatly increased the porosity and permeability of the country rocks, larger volumes of water are able to interact with larger volumes of rock and thereby extract large quantities of metals from them. Probably for this reason, numerous base and precious metal deposits are associated with subaerial calderas, and most volcanogenic massive sulfide deposits appear to be associated with submarine

calderas. Because of these potentially greater volumes of circulating water per unit volume of rock, especially in a submarine caldera environment, heat extraction from intrusive bodies is more rapid and the lives of the hydrothermal ore-forming systems are correspondingly shortened. Perhaps this relatively short life span for submarine circulating hydrothermal systems explains why stratabound massive sulfide deposits in a given district tend to be confined to a geologically narrow time interval.

Circulating groundwaters play two somewhat different chemical roles in ore-forming processes, depending on whether they are the sole ore-transporting medium or they become mixed with ore-transporting fluids from a magmatic source. As discussed previously, the high ore-transporting capacity of magmatic fluids is due primarily to their high chloride content and the fact that metal-sulfide solubilities are generally directly proportional to the chloride concentration raised to a power equal to the stoichiometric coefficient on the chloride ligand. Because of this exponential relationship, mixing with generally lower-salinity groundwaters promotes precipitation of metal sulfides (pyrite, chalcopyrite, sphalerite, galena, argentite), oxides (magnetite, hematite, cassiterite), and perhaps native Au and Ag. The cooling effect of generally lower-temperature groundwaters also promotes precipitation of ores.

Another important chemical role of groundwaters in ore-forming processes is as the sole, or predominant, ore-transporting medium for the formation of many precious and base-metal sulfide deposits (vein, dissemination, and replacement ores) that occur on the peripheries of "porphyry"-type deposits, as well as of most massive sulfide deposits that have been formed in submarine environments. For circulating groundwaters to be effective in producing economic mineral deposits, over a temperature range of about 100–400°C, they must acquire and have transport capacity for approximately 10^2 – 10^4 ppm of S; 10^2 – 10^4 ppm of Fe; 1– 10^3 ppm of Cu, Zn, and Pb; and 10^{-3} –1 ppm of Au and Ag. The required concentrations of H_2S may be acquired by leaching of disseminated sulfides (mainly pyrite) from country rocks at elevated temperatures, by reduction of sulfates from evaporitic sediments, or by reduction of aqueous sulfates in seawater, which contains about 1.7×10^3 ppm total sulfate. Reduction of these various sulfates to H_2S may be brought about by reaction with the ferrous component of rock-forming ferromagnesian minerals and with carbonaceous material at temperatures above about 200°C.

The capacity of circulating groundwaters to acquire requisite concentrations of metals from the country rocks and to transport them is directly dependent on temperature and chloride content but inversely dependent on pH and H_2S content. Seawater contains abundant chlorides (3.5 wt. % NaCl), whereas most meteoric waters are appreciably less saline. However, these latter waters may acquire appreciable salinity by circulation through evaporite-bearing rocks, by reaction with tuffaceous volcanic rocks, or as a residue from boiling. At deeper levels in a circulation system the direction of fluid flow is toward the intrusive heat source. In this regime, increasing temperatures promote exchange reactions between the saline groundwaters and clay minerals or micas in the wallrocks. These exchange reactions release HCl to the circulating fluids, which lowers

their pH and, in turn, enhances their capacity to dissolve and transport metals. The combined effects of increasing temperature and decreasing pH tends to offset the concomitant increase in H_2S fugacity, hence the transport capacity of the fluids continues to increase during the heating stage of the cycle.

During ascent and cooling of these heated, metal sulfide-charged fluids, several processes may operate to precipitate ore minerals. On encountering carbonate rocks, these acid hydrothermal solutions may dissolve the carbonates, become neutralized thereby, and concomitantly precipitate ore minerals. These fluids also may mix with cooler groundwaters at shallow depths, which causes precipitation of sulfide, oxide, and sulfate minerals. In submarine circulation systems, high-temperature "evolved" seawater may be discharged onto the cold seafloor or into unconsolidated sediments to form massive stratabound ores. Under the reduced pressures of near-surface environments the hydrothermal fluids may boil, causing the pH of the residual liquid to rise and, in turn, the precipitation of hydrothermal minerals.

Whether the ore deposits produced by the processes that operate in a groundwater circulation system are Cu-rich or Pb- and Zn-rich, depends to a large extent on the nature of the country rocks through which the waters circulate. Hydrothermal systems developed in rocks, especially volcanic rocks, of felsic composition tend to produce ores rich in Pb, Zn, Au, Te, Sb, As, and Hg, whereas those developed in rocks of intermediate to mafic composition tend to produce ores richer in Cu, Co, Ni, Ag, and Bi.

PRESENT AND POTENTIAL PROSPECTING TECHNIQUES AND PHILOSOPHIES

Techniques and philosophies currently employed in prospecting for late magmatic and hydrothermal ore deposits naturally fall into two categories: (1) those that exist in the public domain and (2) those that are a matter of proprietary concern to individuals or organizations. Obviously, little can be said about the latter category, except to note that our present understanding of ore-forming processes would be much better if freer exchange of ideas and information prevailed throughout the scientific and industrial communities. Regarding the former category, numerous geophysical and geochemical techniques have been employed, in combination with geological investigations, to locate favorable targets for the best tool yet devised—the diamond drill. This same integrated approach, when strengthened by judicious incorporation of fundamentally based concepts of ore-forming processes, offers promise of greater prospecting success in the future.

Doubtless there are potential prospecting techniques currently under development that are not part of the public domain; however, there may be other relationships, deducible from our present level of understanding, that are not now widely recognized as potentially useful in prospecting. Among the relationships that warrant serious consideration are the following:

1. One of the features of those magma bodies with which

extensive hydrothermal activity is characteristically associated is their moderately high H_2O content, reflected in the relatively early crystallization of hornblende and/or biotite at pressures greater than about 500 bars. Thus, the occurrence of phenocrystic hornblende or biotite in an intrusive igneous body may be indicative of extensive hydrothermal activity near its margins. Also, on a regional scale, unmetamorphosed hornblende- or biotite-bearing volcanoclastic rocks may offer clues to the occurrence of compositionally similar intrusive bodies, with which hydrothermal activity may be associated.

2. Another regional geologic indicator of the former presence of H_2O -rich magmas and of possible hydrothermal systems is caldera-type structures produced by explosive volcanism. In a paleomarine geologic setting, these features may provide valuable clues to the existence of massive sulfide deposits, especially near centers of resurgent igneous activity.

3. Chloride-rich, hence potentially metal-rich fluids emanating from a magmatic source tend to produce Fe-rich, Al-poor skarns in nonargillaceous carbonate rocks, whereas just the opposite is true of chloride-poor magmatic fluids. The extent of Fe versus Al metasomatism in carbonate rocks may provide a clue to the metal-carrying capacity of the metasomatizing fluids.

4. Within an already recognized hydrothermal system, examination of fluid inclusions and the S isotope compositions of coexisting sulfide and sulfate minerals may reveal areas where extensive boiling of the hydrothermal fluids occurred. Because the boiling process tends to result in precipitation of metal sulfide, such areas are favorable targets for exploration.

5. Hydrothermal fluids generally alter the oxygen and hydrogen isotopic composition of the rocks through which they pass, hence isotopic mapping of an area of suspected hydrothermal activity may provide clues to hidden ore bodies.

DEFICIENCIES IN UNDERSTANDING MAGMATIC-HYDROTHERMAL PROCESSES

What is currently known about the multitudinous processes involved in the formation of late magmatic and hydrothermal ore deposits and the factors that control them is overshadowed by what remains to be learned. Magmas that give rise to extensive hydrothermal activity, explosive volcanism, or pegmatites evidently are atypical in their anomalously high H_2O contents, but it is not known whether the entire anomaly is produced by magma-generating processes or whether it is enhanced to a large extent by differentiation processes in higher-level magma chambers. It is also evident that to produce the observed hydrothermal alteration patterns and to transport the ore-forming metals and S, hydrothermal fluids derived from these same H_2O -rich magmas must also be rich in Cl. It is not known, however, whether many other hydrous magmas that do not produce extensive alteration and mineralization are anomalously poor in this element. Some Cl-rich hydrous magmas acquire high concentrations of these two critically important elements by largely independent means, but just how they are acquired is not at present understood. It is also apparent in many cases, such as Li-rich pegmatites, Sn-rich granites,

and Cu-rich porphyries, that ore-producing hydrous magmas are anomalously rich in certain metals, but just how these anomalies are produced is again poorly understood.

Waters rich in Cl also appear to be essential for the leaching and transport of metals in those hydrothermal ore-forming fluids that are not derived from magmatic sources. The processes by which convectively circulating waters acquire their high chloride contents (salinities) in a submarine environment are readily apparent, but how similarly convecting meteoric water systems in some subaerial environments acquire their salinities is not completely understood. Nor is it known whether these saline solutions obtain most of their high metal contents from country rocks outside the igneous heat sources or from metal sulfides previously deposited in magmatic-hydrothermal systems.

ORTHOMAGMATIC PROCESSES

Those aspects of orthomagmatic processes that appear to have an important bearing on ore formation, but about which present understanding is inadequate to assess their roles quantitatively, include the following:

1. The physical chemistry of partial melting, especially in terms of (a) the petrology of the source rocks, (b) the mode of occurrence of H_2O and other volatiles, and (c) the partitioning of these volatiles and the ore-forming elements between residual minerals and hydrous melts as a function of melt composition (including H_2O content) and degree of melting.

2. The extent to which magmatic differentiation and convection operate during and following magma emplacement and the effects of these physical processes on the distribution of volatiles and ore-forming elements in a given magma system.

3. The extent to which wallrock assimilation operates in a given geologic setting and its effects on the ore-forming capacity of magmas.

4. The thermodynamics and kinetics of fractional crystallization in cooling hydrous magmas and the solubility relationships of ore minerals in the residual melts.

5. The role of hydrogen diffusion in affecting the redox state of hydrous magmas.

6. The pressure-temperature-composition dependence of the stability of hydrous minerals and their role as possible indicators of magmas with hydrothermal ore-forming potential.

TRANSITIONAL PROCESSES

By definition, transitional processes overlap late orthomagmatic processes. Deficiencies in knowledge of some late orthomagmatic processes constitute deficiencies in knowledge of early transitional processes. A much better understanding of the following aspects of these latter processes is needed:

1. The role that physical properties of different wallrocks in different pressure regimes plays in the separation of the magmatic aqueous phase (second boiling).

2. The mechanics of fracturing in the roofrocks of magma chambers and the extent to which hydraulic fracturing by the magmatic aqueous phase plays a role.

3. The thermodynamics and kinetics of crystallization in multiphase crystal-melt-volatile systems.

4. The effects of increasing internal pressure during second boiling on crystal-melt equilibrium, especially as they pertain to development of mineral zoning in pegmatites.

5. The partitioning of volatile elements, especially S, Cl, and F between magmas and aqueous fluids, and the factors that control it.

6. The partitioning of ore-forming elements between magmas and aqueous fluids and its dependence on fluid composition, pressure, temperature, oxygen fugacity, and magma composition.

7. The manner in which the compositions of magmatic fluids change with evolution from a crystallizing magma.

8. The thermochemistry of magmatic aqueous fluids, especially as it relates to condensation (or boiling) at submagmatic temperatures and pressures, and vapor-liquid partitioning of aqueous species.

5. The manner in which meteoric water and seawater evolve into ore-forming fluids by interaction with wallrocks and as a function of the physical characteristics of the system.

6. The causes for different types of metal associations and ore-mineral zonation in hydrothermal systems.

The above listing of deficiencies in present understanding of magmatic-hydrothermal ore-forming processes doubtless is incomplete, but it serves to illustrate the need for greatly intensified and appropriately focused research efforts on the numerous interrelated geological, petrological, and geochemical aspects of ore-forming processes. At present, there appears to be a bimodal distribution of relevant knowledge, with highs in igneous petrology and low-temperature aqueous geochemistry, and with a distinct low between them. Once this low is filled and the highs are further bolstered, the ore-forming "theme" of Gustafson and Hunt (1975) can, perhaps, be fully orchestrated.

HYDROTHERMAL PROCESSES

Aspects of hydrothermal processes that are poorly understood at present include, but are not limited to, the following:

1. The interaction of aqueous fluids emanating from a magmatic source with wallrocks of different compositions at submagmatic temperatures, especially as it relates to mineral zoning in pegmatites, skarn formation, and hydrothermal alteration patterns.

2. The effects of wallrock interaction on the evolution of hydrothermal fluids with time, especially as they relate to the ore-transporting capacity of the fluids.

3. The dependence of mineral solution, transport, and deposition on pressure, temperature, and fugacities of volatiles, especially of H_2O , H_2S , CO_2 , CH_4 , SO_2 , O_2 , HCl , and other chlorides.

4. The conditions under which fluids from a magmatic source mix with waters from extraneous sources and the effects of this mixing on transport and deposition of ores and wallrock alteration patterns.

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Ores Formed by Diagenetic and Metamorphic Processes

HUBERT L. BARNES
The Pennsylvania State University

SAMUEL S. ADAMS
Fugro Rocky Mountain, Inc., Boulder, Colorado

ARTHUR W. ROSE
The Pennsylvania State University

Diagenesis and metamorphism encompass a wide variety of processes beginning with low-temperature transformations of the chemistry, mineralogy, and textures in newly deposited sediments and extending to very high temperatures and pressures. Extensive migration of fluids and associated solutes during these processes forms several important types of ore deposits, the most valuable of these being sandstone-type uranium deposits, Mississippi Valley-type lead-zinc deposits, and red-bed copper deposits. Such processes also form nonmetallic ores of sulfur, asbestos, talc, tremolite, kyanite, vermiculite, and the abrasives, emery and garnet. In this review, more consideration will be given to the three types of metallic ores for the following reasons. Sulfur deposits associated with evaporites are becoming uneconomic because of their comparatively high energy requirements for extraction and because of competition from by-product recovery from sour natural gas, flue-gas desulfurization, and other sources. In addition, known sulfur resources are vast. Ores of asbestos, talc, tremolite, kyanite, vermiculite, emery, and garnet are found in rocks of predictable metamorphic grade and facies; although the metamorphic and metasomatic processes by which these ores are generated are not thoroughly understood, the probability seems low that re-

finement of such genetic concepts would lead to significant advances in exploration methods or, especially, to major discoveries of ore. Furthermore, competition from synthetic abrasives (carbides) and insulation (fiberglass) and the environmental questions concerning asbestos threaten investments in exploration for these commodities.

The status of knowledge concerning the three types of metallic ores formed by diagenesis and metamorphism is summarized below. The type considered first is the one for which research offers the largest combined potentials for improving exploration, for the discovery of important new deposits, and also for more efficient mining by *in situ* solution extraction.

URANIUM DEPOSITS

Concentrations of U that are almost ore grade occur in several structural settings within igneous, metamorphic, and sedimentary rocks of various geologic ages. Their diverse characteristics have been classified, based in part on genetic interpretations (Kimberley, 1978; McMillan, 1977; Ruzicka, 1977; Cornelius, 1976), into a dozen or more distinct types of U

deposits, but these can be grouped into four or five broader categories. Although some may result entirely from magmatic processes, for example, the peralkaline syenites in Greenland, most deposits appear to be products of some combination of sedimentation, diagenesis, and metamorphism, with or without subsequent enrichment through groundwater processes. The relative importance of various processes in the genesis and controls of these deposits is incompletely understood, but the more obvious empirical characteristics of the deposits have provided a successful basis for exploration. It is axiomatic, however, that an improved understanding of the formation of these deposits would enhance exploration, particularly as exploration concentrates on more remote, poorly exposed, and deeper geologic terrains.

Estimates of current world U reserves are summarized in Table 6.1. The majority of the reserves occur in sandstones, quartz-pebble conglomerates, or metamorphic rocks associated with Middle Proterozoic unconformities. Estimates of undiscovered U resources indicate that these same hosts carry the majority of resources as well, excepting only the large, but very low grade, resources such as the Chattanooga shale of the south and east United States and the shales of the Ranstad area, Sweden. For the deposits found in sandstones and in metamorphic rocks, concepts of ore formation will be reviewed separately.

Current U exploration, development, and mining programs take advantage of accumulated empirical observations and data on the various types of U deposits. In some cases, these data have been used to develop working models and genetic concepts that in turn have improved the interpretation of the basic data. However, the ratio of ore discovered per foot of drilling is decreasing (Blanc, 1975), indicating that improved concepts are needed. In many cases existing data are subject to substantially different interpretations, leading to ambiguities both in the formulation of exploration plans and in the evaluation of geologic data, U mineral occurrences, and ore deposits. To resolve these ambiguities and meet the requirements for both a more accurate understanding of ore genesis and improved resource assessments, studies of U deposits should attempt to define the targets geologically, geochemically, and geophysi-

cally, emphasizing at every opportunity the means for expanding the target size and for remote recognition of mineralization.

DEPOSITS IN SANDSTONES

Most sandstone deposits occur in continental, arkosic sandstones interbedded with, or adjacent to, bentonitic shales. The shales are generally believed to contain volcanic ash from which the U in the sandstones could have been derived. In addition, leaching of uraniferous granites also provides a viable U source for some of the sandstone deposits, for example, the Tertiary basins in Wyoming. In some important respects, each of the major U districts of the United States have distinctive characteristics.

The important tabular U deposits of the Grants Mineral Belt, northwest New Mexico, occur within two sandstones of the Jurassic Morrison formation. Smaller deposits occur within sandstones of a bentonite-rich shale that separates the two principal ore sandstones. These deposits contain abundant epigenetic carbonaceous (humic) material that is likely derived from the destruction, mobilization, and re-precipitation of detrital plant debris. Uranium is intimately associated with this carbonaceous material except where the latter has been destroyed by the subsequent incursion of oxygenated groundwaters forming roll-front-like deposits. The deposits, therefore, are presumably related to the humate masses that provided loci for the absorption and precipitation of U from groundwaters within the permeable sandstones. Whether the U was derived from the adjacent bentonitic shale or was introduced from outside the formation is not known with certainty, but the juxtaposition is circumstantial evidence.

The roll-front deposits of the Tertiary basins of Wyoming are related to the interface between oxidized and reduced sandstone, as shown schematically in Figure 6.1. Various lines of evidence indicate that oxidized water moved through hematite-stained aquifers into rocks containing pyrite or biogenic debris, where reduction processes precipitated U near the boundary between oxidized and reduced sandstones (Rackley, 1976). The mechanism of precipitation appears to involve reduction of dissolved U, occurring as complex ions such as $\text{UO}_2(\text{CO}_3)_2^{2-}$,

TABLE 6.1 Distribution of World Uranium Reserves by Type of Deposit in Thousands of Metric Tons^a

Country	Sandstone	Proterozoic Unconformity	Quartz Pebble Conglomerate	Migmatite Complex	Other	Total
United States	586				31	617
Canada		73	117	8		198
South Africa			222			222
Southwest Africa				103		103
Australia	28	346	—	—	81	455
Other	172	24	—	—	145	341
TOTALS	786	443	339	111	257	1936

^a Available at approximately \$30 per pound of U_3O_8 forward cost. Exclusive of Soviet-bloc countries. Modified after Wright (1977) and Nuexco Uranium Seminar (1977).

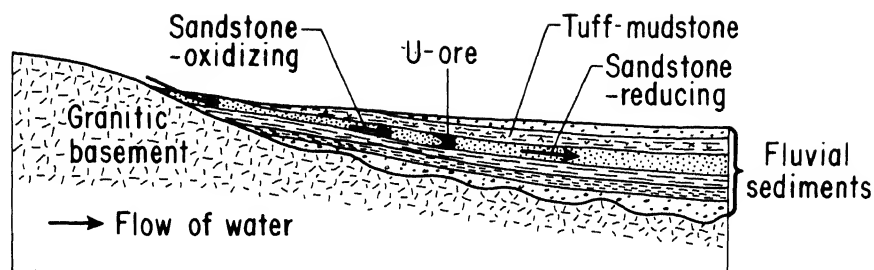


FIGURE 6.1 A schematic diagram of the geologic environment present during the formation of sandstone-type U deposits.

by organic material, pyrite, or marcasite and perhaps by metastable sulfur species such as sulfite and thiosulfate (Granger and Warren, 1969). Carbonaceous material does not become enriched within the roll-front deposit itself. As with most sandstone-U deposits, the roll fronts of the Gas Hills, Crooks Gap, Powder River Basin, and Shirley Basin are spatially related to volcanic-rich sediments of the overlying White River Formation. It is noteworthy that these districts are distributed more or less around the Granite Mountains, which contain relatively uraniferous and deeply leached granites. Although field relations generally support the formation of the deposits through the reduction and precipitation of U from oxidized waters, the specific source of the U remains poorly defined.

The U deposits of the Texas Coastal Belt occur principally within Tertiary beds below and above (and sometimes within) a bentonite-rich formation. Most deposits occur at, or close to, the boundary between oxidized (up-dip) and reduced (down-dip) sandstone. Habits of the deposits are in some cases clearly roll-fronts, whereas in other places they assume more tabular forms and appear to have had more than one stage of development. Pyrite is present and in some cases abundant. The amount of carbonaceous material in ore varies from relatively abundant to none, in which case sulfide is abundant. Unlike the Wyoming roll-front districts, some deposits in Texas are related to normal faults parallel or subparallel to the Gulf Coast. Sulfur isotope data suggest that H_2S has been introduced from underlying formations into the sandstones along these faults, thereby producing pyritiferous reduced zones against which U deposits were precipitated from more oxidized groundwaters.

Other important sandstone-U deposits occur in the Colorado Plateau and Basin and Range Provinces within arkosic sands that are, or were, permeable and that occur in juxtaposition to volcanic-rich sediments. Some contain significant amounts of V (Uravan Mineral Belt). Detrital or remobilized carbonaceous material is present in most of these deposits. In summary, sandstone-U deposits appear generally to have formed through precipitation of U from moving groundwaters carrying oxidized U, probably as carbonate complexes, by reduction with detrital carbonaceous material, remobilized humates, or H_2S . With the exception of the deposits of the Texas coastal region, the reductant appears to have been indigenous to the ore-bearing formation. Proximity to volcanic-bearing sediments suggests that they were the source for the U.

The empirical observations and tentative genetic models for sandstone deposits described above are providing a useful basis for current U exploration. The genetic understanding of most of these deposits, however, is sufficiently incomplete that target areas may either be overlooked or may be the object of inefficient exploration. Gaps exist in knowledge of compaction, dewatering, and alteration of the bentonitic sediments that are the probable sources for the U. Also unknown is the duration of processes of U concentration into mineable deposits. Because of the low solubility and low abundance of U, ore concentrations imply transport by substantial quantities of groundwater, requiring a stable, but dynamic, groundwater system. Consequently, the diagenesis, lithification, alteration, and hydrology of continental sedimentary basins are particularly important and deserve expanded study.

The chronologic sequence of events is also uncertain. Is pre-concentration into enriched source rocks necessary prior to the formation of ore deposits? The significance of prestructural and poststructural events and the importance of the time of structural development need to be clarified. Are there significant U concentrations that formed entirely after diagenesis and lithification of the host sediments?

DEPOSITS IN METAMORPHIC ROCKS

Two important types of U deposits occur in metamorphic rocks. Examples of the first type, the Proterozoic unconformity and strata-related types, are the Alligator Rivers district, Northern Territory, Australia, and the Athabasca region of northern Saskatchewan, Canada. Both deposits occur in lower Proterozoic metamorphic rocks immediately below a middle Proterozoic unconformity. These deposits constitute approximately 23 percent of the current world reserves (see Table 6.1). The second type, the migmatitic type, includes the Rossing deposit in southwest Africa and the deposits in the vicinity of Johann Beetz, Quebec, Canada, which are typical of deposits occurring in metamorphic terrains that have experienced deformation and partial melting as evidenced by the development of migmatites, pegmatites, and granites. Other occurrences of U in metamorphic rocks are insignificant when compared with these two types of occurrences.

The deposits related to the lower-middle Proterozoic unconformity generally occur immediately below an unconformity

within structural shear or fault zones along which amphibolite-grade rocks have commonly undergone retrograde metamorphism to chlorite-bearing assemblages (see Figure 6.2). The host rocks are generally linear or pod-shaped within the structural zones. The principal U-bearing phase is uraninite. Gold is locally an important accessory mineral in the Alligator Rivers district, whereas Ni, As, and Ag are important in some of the deposits of northern Saskatchewan. These deposits generally "bottom out" with increasing depth below the unconformity, although the Jabiluka deposit in the Alligator Rivers district extends below the unconformity several hundred feet within the same stratigraphic horizon. The deposits range in size up to more than 400 million pounds of U_3O_8 at grades from 0.20 to more than 2 percent U_3O_8 (Nash, 1978). Recent exploration activity in the Athabasca region has identified substantial mineralization within the overlying unmetamorphosed and generally undeformed middle Proterozoic clastic sandstones. A several-foot-thick zone within the lower Proterozoic metamorphics immediately below the unconformity and containing much of the ore is interpreted to be a regolith zone.

Numerous isotopic dates near 1000 million years (m.y.) for ores from these two districts indicate that the most recent important mineralizing events occurred well after the middle Proterozoic (Knipping, 1974). Other dates, extending back to approximately 2 billion years, suggest a long period of intermittent remobilization. Although recent and important mineralizing events occurred after the period of middle Proterozoic erosion and sedimentation, it is unclear what events occurred prior to these events and what significance they hold for the genesis of these deposits. One school of thought attributes the formation of the deposit entirely to groundwaters circulating during and following the middle Proterozoic erosion, weathering, and sedimentation. Others suggest that these middle and late Proterozoic events further concentrated U occurrences that were formed during the lower Proterozoic period of metamorphism. The strata-related deposits, such as Beaverlodge and Jabiluka, therefore may be precursors through dissolution, redistribution, and enrichment to those that are directly related to the unconformity. This question has not been resolved and is an important subject for future research.

Deposits in high-grade metamorphic rocks, the migmatitic type, are found in deformed, lower Proterozoic sediments containing local to widespread occurrences of pegmatite or alaskite masses. These rock types may be cut by later igneous rocks

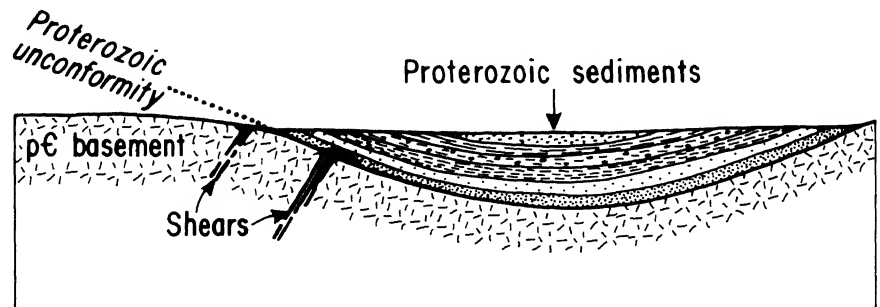
that are generally barren of U. Uraninite is reportedly the principal radioactive phase that occurs in the pegmatite or alaskitic bodies. The deposits in Quebec are low grade, generally in the range of 0.035 wt. % U_3O_8 . The Rossing deposit, southwest Africa, is locally somewhat higher grade, possibly because of secondary enrichment. These deposits are apparently the result of metamorphism, partial melting, and the fractionation of U into the pegmatitic or alaskitic phase. There is some evidence that the source sediments in the two districts are of similar age. However, data on the U content of the original sediments and on processes of concentration are lacking.

The empirical observation that major U deposits occur at, or below, the unconformity at the base of the middle Proterozoic is ample justification for concentrating exploration on rocks of that age. Why this particular hiatus and its associated lithologies, deformation, alteration, and metamorphism should be so productive needs to be investigated through a series of carefully designed research projects. Careful mapping and descriptions of the deposits are gradually becoming available and will provide the necessary basis for successful research. Within this geologic, structural, and mineralogic framework the specific physical and chemical ore-forming processes can be decoded, leading to the development of improved exploration criteria. Geological arguments related to the evolution of the earth's atmosphere suggest that favorable environments may be of specific ages.

Detailed field studies of the large, low-grade deposits that occur in terrains of migmatization and partial melting should improve exploration for these types of deposits. Although low grade, the size of these deposits makes them amenable to large-scale mining operations or possibly *in situ* leaching techniques. Successful exploration and exploitation will, however, only be realized when the occurrence, distribution, and mineralogy of the deposits is better understood and predicted with a greater success.

Quartz-pebble conglomerates that contain Au and U deposits, such as Blind River, Canada, and the Witwatersrand in South Africa, are largely the result of sedimentary processes. However, the precise history of the U accumulation in these sediments is less convincing than for the Au content and there is evidence that postdepositional processes were crucial in the development of the U-ore deposits. The important U-bearing phase, brannerite, in the Blind River deposits is clearly of

FIGURE 6.2 A schematic diagram of the structural position of many Proterozoic U ores.



postdepositional origin. The importance of postsedimentary processes in the development of these deposits needs to be resolved.

DESIRABLE GENERAL RESEARCH ON URANIUM ORE GENESIS

The identification of crustal U "hot spots" or provinces is an obvious subject for trace-element studies. Can hot spots be identified, and, if so, what is the global tectonic setting in which they occur and might they imply where new provinces could be discovered? Besides spatial effects, another important dimension is time: are there periods when U concentrations appear to have been more widespread than during others? In a general way, U appears to have an affinity for lower Proterozoic sedimentary and metasedimentary rock, middle Proterozoic granites, and Mesozoic and Tertiary continental clastic and volcanoclastic sediments. Furthermore, the regions of Mesozoic and Tertiary occurrences seem to coincide with higher concentrations of U in Precambrian basement rock.

Uranium is mobile in oxidizing aqueous solutions and much less so in reducing solutions. Available thermodynamic data (Langmuir, 1978) show that transport in groundwater may be by uranyl fluoride, phosphate, or carbonate complexes, but further experimental evaluation is needed to confirm the importance of phosphate complexes and to consider humate complexes. The relative importance of carbonate and hydroxide complexes and the solubility of U minerals at high temperatures is largely unknown and deserves extensive research (Rich *et al.*, 1977). The effects of sorption of aqueous U species on ferric oxyhydroxides, clays, and other solids is apparently important as a precursor to reduction and in limiting U mobility. Therefore, the extent of U sorption and related kinetics require better definition as contributors to ore formation.

Research on aqueous reactions affecting U mobility offers a second dividend in addition to better defining the geologic environments where ore concentrations might be deposited. *In situ* leaching, now largely dependent on empirical testing, could be better designed using the resulting reaction data. It is clear that leaching of U, as now used in Texas, will become increasingly important because it allows economic recovery from deposits that could not support conventional mining. However, the lixiviant must not become depleted through extraneous reactions and must remove U from the rock without destroying natural or induced permeability. Thorough knowledge of rock mineralogy and interactions with leaching solutions will be required if this method is to become widely developed.

MISSISSIPPI VALLEY-TYPE DEPOSITS

These deposits have long been the source of most of the Pb, much of the Zn, Cd, Ga, In, Ba, and Fl, and some of the Cu, Co, Ni, and Ag production of the United States. Although Pb and Zn are the dominant metals produced (see Table 6.2), the comparatively simple mineralogy of these ores favors the re-

covery of other metals occurring at even trace levels. The newest of the producing districts in Table 6.2, the Viburnum Trend in Missouri (Special Issue Devoted to the Viburnum Trend, Southeast Missouri, 1977), contains the largest Pb and Zn reserves of the United States and is producing significant quantities of Cu, Ag, and Cd. It contributes 85 percent of the current production of Pb in the United States and 15 percent of the world's total. The relatively recent discovery of this highly productive district, during 1955–1965, gives encouragement that other major districts of this type remain to be discovered and justifies both further research on exploration methods and intensified exploration. Indeed, the promising developments in the even newer Central Tennessee District confirms that further exploration for this ore type is warranted.

GENESIS OF MISSISSIPPI VALLEY-TYPE ORES—A MODEL

This type of deposit is restricted to ores containing sphalerite, galena, barite, marcasite, pyrite, and small quantities of Cu minerals. Generally, fluid inclusions are highly saline and may have filling temperatures up to 250°C. Isotopically, the S is heavy and the Pb is anomalous with model ages typically younger, but sometimes older, than the host rocks. Host rocks are usually carbonates, although both shales and sandstones may enclose these ores. Their distribution may be either rigidly stratabound, as in Mirgalimsai, Kazakhstan, or generally stratiform as in Illinois–Wisconsin. A variety of these deposits is described in Wolf (1976).

Paleogeographic reconstructions reveal that these deposits were formed along the margins of miogeosynclines, sometimes syngenetically in carbonates within the basin but more often in shallow older carbonate rocks or sandstones on the adjacent shelf up to a few score kilometers outside the syncline. This spatial association with major basins can also be shown to be temporal where such evidence exists, and both imply a genetic association, presumably with hydrothermal solutions expelled during maturation of the sediments filling the basin. This process continues for about 10–20 m.y. after burial (Hunt, 1979). During compaction, diagenetic alteration, and burial metamorphism at depths of a few kilometers, large quantities of water flow from the sediments as a consequence of both osmotic pumping and dehydration reactions. Temperatures in the sediments may sometimes exceed 250°C (Tissot and Welte, 1978), but most waters are released at lower temperatures. Because marine sediments may contain evaporites and are generally organic-rich, these hot (approximately 100–200°C) solutions are highly saline (typically 10–30 percent; Hanor, 1979) and reducing (organic-rich) in agreement with evidence from fluid inclusions in ore minerals. Flow of these solutions up-dip toward and beyond the margins of the basins is caused by pressure gradients (from lithostatic to hydrostatic).

There is evidence that flow may extend considerable distances. First, it is required for districts of the dimensions noted in Table 6.2. In addition, the anomalous Pb isotope ratios of the ores indicate that the solutions often pass through large volumes of sediments on their paths to sites of ore deposition

TABLE 6.2 Ores of Major Mississippi Valley-Type Deposits of the United States

District	Dimensions	Ore Production Plus Reserves (millions of metric tons)	Average Ore Grade	
			% Pb	% Zn
Austinvile, Va.	10 km long	25	0.7	3.7
Eastern Tennessee	25 km long	50	Minor	4.0
Illinois-Wisconsin	10,000 km ²	100	0.5	5.0
Southeast Missouri (Old Lead Belt)	Several hundred km ²	340	3.0	Minor
Southeast Missouri (Virburnum Trend)	72 km long 5 km wide	Several hundred	6.0	1.0
Tri-state	5000 km ²	500	0.6	2.3

(Doe and Zartman, 1979). They further suggest that the ore metals were extracted from sedimentary rocks along their flow paths. This offers an explanation for the widely variable Pb/Zn ratios of these deposits in that shales or micaceous and argillaceous sandstones should contribute higher Zn contents and feldspathic sandstones should contribute higher Pb contents when leached by reduced ore solutions.

Mississippi Valley-type ores were deposited in two different environments. Some are formed syngenetically in submarine, nearshore facies, as in argillaceous carbonates or carbonate-rich shales at Mirgalimsai, Kazakhstan (Smirnov, 1977). More common are those in near-syncline shelf carbonates as in the epigenetic ores of southwest Wisconsin. Because reefs develop in coastal waters, these rocks are occasional hosts for ore deposition, as in southeast Missouri and Pine Point. Gravity "thrust" faulting is not uncommon in such nearshore facies of subsiding basins, so it is not surprising that such post-ore faults occur in the host rocks of some of these deposits, such as Mirgalimsai and Appalachian deposits. These environments are shown schematically by Figure 6.3.

The mineralogy of the ores restricts possible transport geochemistries. Ubiquitous early dolomitization preceding sulfide deposition is consistent with the high Mg content characteristic of solutions present during initial diagenesis of marine sediments. Common corrosion of galena and sphalerite, most obviously along growth bands, shows that the degree of saturation of the ore solution changed frequently and that the depositional reactions were easily reversible, implying thereby that rapidly reacting aqueous complexes were responsible for ore transport. Thermodynamic evaluation of the mineral assemblages present (Giordano, 1978) suggests that the saline ore solution contained S dominantly as bisulfide but that neither bisulfide complexes nor chloride complexes provide adequate solubilities to account for transport of galena; consequently, we recognize that organic complexes of Pb may have been dominant. With currently available data, complexing of Zn may be by either bisulfide or, perhaps, organic ligands but not by chlorides. The constancy in thickness of synchronous growth layers within all crystals of the well-banded sphalerites throughout the Southwest Wisconsin District indicates that at any one stage of deposition, the concentration in the ore solution and the rate of deposition

were virtually the same throughout this district. Therefore, deposition sufficient to reach ore grade was not caused locally by exceptionally high concentrations in the ore solution nor by an unusually long period of deposition but by simultaneous deposition at an unusual concentration of sites (McLimans *et al.*, 1980).

Causes of ore deposition are implicit in ore textures and mineral distribution. The paragenetically late occurrence of barite with and above the ores suggests that oxidation accompanied deposition. The alteration of clays to microcline plus sericite (Heyl, 1968) along ore channels and the alkali content of fluid inclusions in the ores implies that the ore solutions were weakly alkaline during transport. However, common dissolution of host carbonates during ore deposition demonstrates that at this stage the solutions had become acidic. The reactions accompanying oxidation of a bisulfide solution may both precipitate sulfide and increase acidity. Such oxidation could be caused by mixing of the reduced ore solution with oxygenated groundwaters. This hypothesis is supported by the variability in D/H in fluid inclusions in the ores (McLimans, 1977) and also by the narrow vertical interval of 15–60 m within which the Wisconsin and most other such ores were deposited.

Because this evolving model still contains some unyielding, serious gaps in general understanding and in precise definition of the genetic process, it remains only a general guide for mineral exploration. For example, it is not yet certain which complexes are responsible for the transport of the metals of these deposits nor, correspondingly, which are the specific causes for their deposition (Barnes, 1979). Similarly, the reasons for the large variation in Pb/Zn contents of these ores remains unresolved. We are also uncertain as to the stage of basin evolution when (and if) ore solutions are released. The duration of the ore-forming processes is approximated only on the basis of dispersion gradients that indicate mineralization in Wisconsin required 250,000 years to form major ore bodies (Lavery and Barnes, 1971). This is a short period compared with that required for dewatering of more recent sedimentary basins, where most flow of solutions seems to have taken place during an interval about 5–10 m.y. after deposition of the basin sediments. If the duration of ore-solution flow were better fixed, then we would know precisely in what age of carbonates,

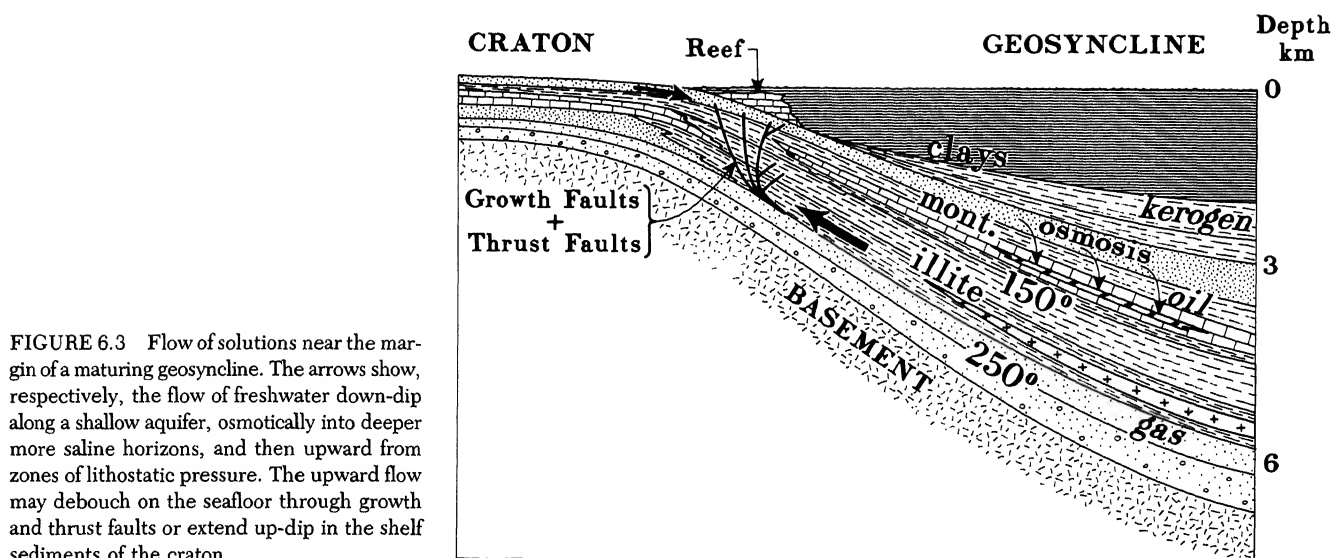


FIGURE 6.3 Flow of solutions near the margin of a maturing geosyncline. The arrows show, respectively, the flow of freshwater down-dip along a shallow aquifer, osmotically into deeper more saline horizons, and then upward from zones of lithostatic pressure. The upward flow may debouch on the seafloor through growth and thrust faults or extend up-dip in the shelf sediments of the craton.

relative to those in the basin, we should search for deposits of this type.

Little information is available on the hydrology of the flow of fluids through such basins. Both hydrologic and paleohydrologic studies of geosyncline evolution would provide important clues as to the structural localization of these ores relative to the source basin. Better characterization of the organic content of both the argillitic beds near these ores and of the fluid inclusions in the ores would also provide a sensitive indicator of the origin of these deposits and a powerful test of this model as a basis for prospecting.

RED-BED COPPER DEPOSITS

Red-bed Cu deposits typically occur as lens- and pod-shaped bodies containing Cu sulfides in local reducing zones within red (hematitic) shale and sandstone (see Figure 6.4). Examples

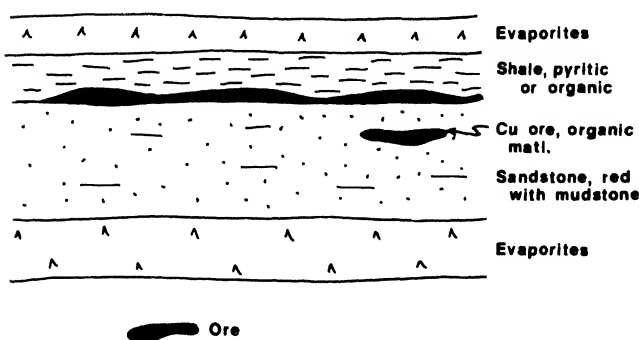


FIGURE 6.4 Lens-shaped red-bed Cu deposit in red sandstone and more extensive "sedimentary" Cu deposit in reducing shale overlying redbeds.

of red-bed deposits include Corocoro in Bolivia and Naciminto in New Mexico. The ores usually contain appreciable amounts of Ag. Occurrences are numerous, but if the term is used in a restricted sense, most are small and production has been minor.

Red-bed Cu deposits are significant because their origin may be closely related to "sedimentary" Cu deposits in shale and sandstone, such as the Kupferschiefer in Germany and Poland, the Zambian deposits, the Dzhezkazgan deposit in the U.S.S.R., and the White Pine deposit in Michigan. Such deposits account for about 22 percent of the Cu production of the non-Soviet world and probably furnish a substantial proportion of Soviet production. The future reserves in these deposits are also large, the Zambia-Zaire deposits alone forming 15 percent of total world Cu reserves (Cox *et al.*, 1973). Discoveries in recent years of major deposits in Poland, small deposits in Oklahoma and Texas, and possible deposits in the Belt series of Montana and in Precambrian rocks of northern Canada suggest a favorable potential for such deposits. At present, exploration in stratigraphic zones like the Belt series of the northwestern United States requires a great deal of drilling and is incomplete because the origin and controls of ore distribution are not understood. Improved knowledge of the characteristics and the processes of mobilizing Cu during diagenesis would make exploration much more efficient.

THE RELATION OF RED-BED AND "SEDIMENTARY" COPPER DEPOSITS

The narrowly defined deposits of the red-bed type appear to have formed from warm chloride-bearing groundwaters or brines that circulated through red (oxidized) sediments, leaching Cu from their host until they encountered a reducing zone created by a concentration of leaves, logs, or other biogenic organic material. The Cu was then precipitated either by reduction of sulfate or by reaction with Fe sulfide to form chalcocite, chalcopyrite, bornite, and related Cu sulfides. Textural evidence

indicates that precipitation of Cu sulfides occurred after deposition of sediments but before deep burial (Rose, 1976). Transport and deposition from chloride-bearing groundwaters are indicated by the greatly enhanced solubility of Cu in a variety of chloride complexes formed in saline groundwaters and by an association of the deposits with evaporites that could have supplied the chloride, as shown schematically by Figure 6.5.

The much larger "sedimentary" Cu deposits like the Kupferschiefer of western Europe share many of the characteristics of the red-bed deposits. They contain similar Cu and Cu-Fe sulfides; they occur adjacent to red, terrestrial sandstones; and they are commonly associated with evaporites or with marine-nonmarine transitions where chloride-bearing seawater or connate waters may have been mobilized during deposition or compaction. Sulfur isotopes in both types show a wide range of values suggestive of partial reduction of sulfate at relatively low temperatures.

A key piece of evidence for a similar origin is the recognition that the Cu-bearing zone at the White Pine deposit in Michigan cuts irregularly across the bedding of the enclosing siltstone (Brown, 1971; White, 1971) and has other geometric features expected for deposition from waters migrating upward from underlying red sandstones. This rather typical "sedimentary" Cu deposit is now generally agreed to have formed by replacement of syngenetic pyrite by Cu-bearing connate fluids forced by changes in hydrology to flow through the siltstone (nominally a shale). More recently, Rentzsch (1974) has demonstrated that the Cu-rich portions of the Kupferschiefer cut across the bedding of the formation and lie on top of oxidized hematitic sandstones that appear to have formed by upward flow of oxidizing waters from below. Whether these waters were flowing at the time of deposition or later has not been established. The Dzhezkazgan deposit also cuts across the bedding.

Current evidence suggests no clear distinction between processes forming the lens-like, red-bed Cu deposits and the stratiform "sedimentary" Cu deposits. Careful geologic studies, like those made at White Pine, are needed to establish the geometric relations of other "sedimentary" deposits to the enclosing hosts and other geologic features. If they prove to be formed by flow of diagenetic or connate fluids, then exploration can focus on sedimentary and structural environments in which such flows of diagenetic waters might be concentrated and where reducing environments might be encountered.

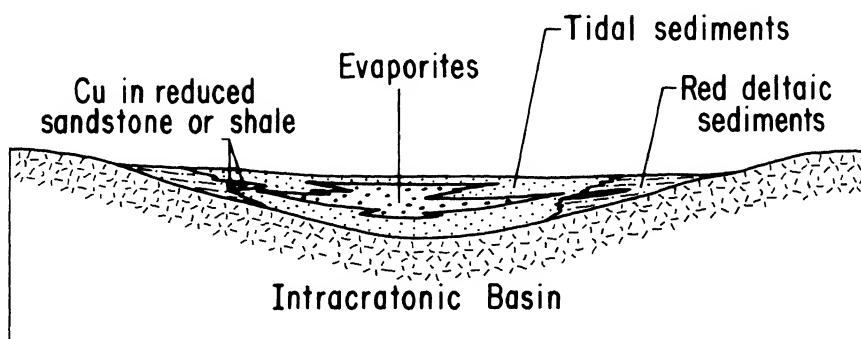
Some workers have suggested that formation of red-bed and "sedimentary" Cu deposits is promoted by availability of Cu-enriched source sediment, by source terrains containing older Cu deposits, or by conditions during certain geologic periods. Others have indicated that under the right conditions, almost any sedimentary pile contains adequate Cu to form ore deposits. If an enriched source is really important, then widely spaced samples of rock or sediment might be used to search for geochemical provinces favorable for the occurrence of red-bed deposits. If the conditions are crucial to the concentration of Cu in a normal sedimentary section, then an improved knowledge of the factors controlling mobilization of Cu from sediments is needed. Currently, there are at least three genetic factors needing evaluation.

1. The "sedimentary" Cu deposits are especially large and well developed in rocks of Proterozoic (Middle Precambrian) age, perhaps because of a change from a reducing to an oxidizing atmosphere during that period (Cox *et al.*, 1973, pp. 172-176). The very large Zambian and Udokan (U.S.S.R.) deposits and the Beltian occurrence in the United States are of this general age. Although it is clear that ore deposition in younger rocks is possible (Late Precambrian at White Pine; Permian at the Kupferschiefer and in Oklahoma), a better understanding of crustal evolution and of the ages of known deposits could focus exploration on rocks of ages that potentially contain the largest deposits.

2. The red-bed and "sedimentary" Cu deposits are generally associated with terrestrial arkosic sediments on platforms or in downwarps within the continent. Whether they are restricted to these environments or if other sedimentologic or tectonic factors may be crucial to their origin is not yet clear.

3. Studies of modern environments are needed to determine whether there is some condition under which major amounts of Cu can be accumulated by direct precipitation from seawater or related fluids. For example, one hypothesis applied to the "sedimentary" deposits has been an origin in a "sabkha" environment, where evaporation from sea-level carbonate deposits leads to upward movement of water, high salinities, and an environment in which metal-bearing solutions can encounter sulfide-rich traps (Renfro, 1974). Research on modern sabkhas and on possible methods of mobilizing and depositing Cu and other metals in such environments might be fruitful and

FIGURE 6.5 Loci of deposition of Cu mineralization at the interface between oxidized, hematitic sandstones or shales and reducing sediments, in vicinity of evaporites.



might help decide whether this environment is crucial in the origin of "sedimentary" Cu deposits.

Detailed studies of the geology, mineralogy, and geochemistry of most of these deposits are lacking but are needed to establish criteria to guide the selection of terrain for exploration and to assist in recognizing rocks near the deposits so that evidence of proximity can be recognized during exploration and drilling. Such studies should encompass the entire paleo-hydrologic regimen and not just the conditions within known ore bodies.

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Weathering as Ore-Forming Processes

SAM H. PATTERSON
U.S. Geological Survey

INTRODUCTION

Weathering processes are those that alter rocks, minerals, and soils in the earth's crust within the zones of influence of the atmosphere, hydrosphere, and biosphere (Carroll, 1970; Loughnan, 1969; Keller, 1975). Weathering processes form, modify, and ultimately destroy many types of mineral deposits and soil, both of which are essential materials for civilization. These processes are classified into mechanical and chemical groups. Mechanical weathering consists mainly of the disintegration of rocks by penetrating roots, burrowing animals, alternating expansion and contraction by diurnal thermal cycling, and freezing and thawing. Mechanical weathering improves the access and effectiveness of the agents of chemical weathering. The major roles of the atmosphere and biosphere are their influences on the chemistry of water, the principal agent of weathering. The atmosphere contributes oxygen, carbon dioxide, and nitrogen and transports other elements and water. Plants remove mineral matter from soil and rock by extracting nutrients through their root systems. Minor chemical alteration of soils and shallow rocks by the atmosphere takes place, and some material is removed in vapors. Plants

and microorganisms greatly influence the acidity-alkalinity and oxidation-reduction conditions of water in the rocks and soils with which they are in contact during their life cycles and leave decaying organic matter that further changes the chemistry. They, therefore, may have significant influences on whether minerals are being leached or precipitated. The dominant movement of water is from the surface downward, and definitions of weathering generally include this idea. However, water moving laterally or even upward in artesian flow or by evapotranspiration may contribute to the formation of ore. The alteration of rocks by water moving downward from the surface is called the "supergene process," but this term is interchangeable with weathering only in a general way.

The depths to which weathering progresses are controlled by several limiting factors. Weathering processes cease where downward moving water intermixes with upward moving heated water. In such zones, weathering and hydrothermal processes overlap and their products may be difficult to distinguish. The water table is also commonly said to terminate weathering, because circulating water and oxygen are required to alter minerals by these processes and remove the components being leached. The water table limitation is not universally applica-

ble, because in many places the water below it is circulating and contains oxygen. The zone below the water table is also locally favorable for the precipitation of elements leached from overlying rocks and is therefore important in the formation or enrichment of some mineral deposits. Little reliable information is available on the depths to which weathering can penetrate. In regions of heavy rainfall in the tropics, weathering can form ore to depths of several tens of meters. Where the water table is deep, oxidation can occur at considerable depths; it is reportedly as much as 1400 m below the surface at the Tsumeb mine in South Africa. At this locality, "a rare plumbing accident of nature" (Weber and Wilson, 1977) provided exceptionally deep movement of water in permeable rocks.

The principal conditions favoring the formation of mineral deposits by weathering are (1) the presence of rocks containing a high proportion of soluble minerals, yielding residues rich in sought-for minerals; (2) effective rock porosity, permeability, and drainage, enabling free circulation of water; (3) abundant rainfall alternating with dry periods; (4) prolific developments of vegetation and bacteria; (5) tropical or at least warm climate; (6) low to moderate topographic relief allowing fluctuation of the water table and a minimum of mechanical erosion; and (7) land forms having stable histories, providing time for weathering to be active. This list at best outlines conditions only in a general way, and weathering can form ore in short intervals of geologic time even where some of them are opposing factors. For example, the Ni laterite-saprolite deposits in New Caledonia formed under the favorable conditions of soluble minerals in permeable parent rocks containing Ni, heavy rainfall, and hot climate, even though high relief and tectonic instability tended to increase erosion and shorten the time for weathering to take place.

The processes of chemical weathering have been continuously active since water first appeared at the earth's surface, but the processes certainly changed as green marine plants created an oxygen-bearing atmosphere more than 2 billion years ago and again as land plants developed during the mid-Paleozoic. Precambrian bauxites in the U.S.S.R. are among the oldest mineral deposits formed by weathering. Some of the Precambrian Fe deposits also are thought to have been oxidized and enriched. Bauxite formed by weathering during Devonian time in Russia, during the Late Carboniferous in China, and during the Cretaceous in Europe. Bauxite formed in Arkansas during the Late Paleocene and Eocene and in Oregon during Miocene time, and deposits in Pacific islands are forming today. Refractory clay deposits underlying coal beds, which are themselves proof of prolific vegetation and extensive soil development, formed during Pennsylvanian and Cretaceous periods in the United States. The large laterite bauxite deposits in tropical countries are related to the present land surface and are Late Tertiary and younger in age. Most Ni and Mn laterite deposits are also young.

Mineral deposits are formed by weathering in several different ways. The concentration takes place both by removal of the diluting materials and migration and enrichment of elements to form ore. Minerals formed by weathering are commonly more susceptible in extractive metallurgical processes than those in the parent rock—a critical economic factor. In a

few deposits, the principal effect of weathering is merely the softening of the host rock, making it simpler to separate the desired minerals.

TYPES AND IMPORTANCE OF DEPOSITS

DEFINITIONS

Scientists having different interests, backgrounds, and objectives have proposed many classifications of weathered materials, all of which have shortcomings. This report neither introduces new terms nor advocates any specific classification. Rather, it employs terms having widest usage in the literature.

Laterite-Saprolite

Laterite is a term introduced in India in 1807 for an earthy, ferruginous building material occurring near the surface. The term has been modified with many different meanings in its long, confusing history (Maignien, 1966). According to most definitions used by soil scientists, the material must be rich in secondary hydroxides or oxides of Fe or Al or both. Some require that laterite be indurated, and others include material that hardens with setting and drying. Geologists commonly broaden the usage of the term to include other metals and saprolite, which is a soft, decomposed rock in which many, if not virtually all, of the minerals of the parent rock have been replaced by others formed during weathering. Typically, laterite grades downward into saprolite with deepest penetration of weathering along joints and other zones favorable for water movement. Saprolite retains the textures and structures of the parent rock, and little change of volume take place as it forms. In laterite, the original textures and structures have been destroyed, and commonly there is evidence of loss of volume in its formation. In application of the term laterite to mineral deposits, geologists retain the concepts relating to high Al and Fe contents of other usages and include ores of other metals as well. Most of the world's Al and Ni and some of the Mn and Fe resources are in laterites. Some of the Al and Mn and much of the Ni in weathered deposits is in saprolite. Examples of the diverse application of the terms are to be found in several papers describing Ni in saprolite, published in a volume of a laterite symposium (Evans *et al.*, 1979).

In this report, laterite-saprolite will be used as a group term, and each term will be used separately where applicable.

Oxidized and Enriched Deposits

The oxidized and enriched group includes deposits that have formed by leaching and redeposition and residual enrichment. The process functions in some deposits, such as porphyry Cu, by oxidizing disseminated sulfide minerals and releasing the metal, which is transported downward by groundwater and precipitated in lower zones. The precipitation enriches the disseminated Cu mineralization in the lower zone to form or upgrade ore. Oxidized and enriched porphyry Cu and other types of sulfide are therefore characterized by (1) and upper-

TABLE 7.1 Estimated Proportions of Total U.S. and World Production and Resources of Minerals Formed by Weathering and Potential for Satisfying Long-Range Demands^a

	U.S. Production			U.S. Resources ^b			World Production			World Resources ^b			Potential for Satisfying Long-Range Demands
	Laterite-Saprolite	Oxidized-Enriched	Miscellaneous	Laterite-Saprolite	Oxidized-Enriched	Miscellaneous	Laterite-Saprolite	Oxidized-Enriched	Miscellaneous	Laterite-Saprolite	Oxidized-Enriched	Miscellaneous	
Barite			X			X			x			x	x
Bauxite ^c	XXXX ^d		X	XXX		X	XXX		XX	XXXX		X	XXXX
Copper		XXX			XX			XX			X		X
Gallium	XXX	x		X	x		XXX	x	X	XXXX	x	X	XXX
Gold	x	X	XXX	—	X	X		x		—	X		x
Iron					X		—	XXX		X	XXX		XXX
Lead		X			XX			X			XX		XX
Manganese		X			X	X	XX		X	XXX	X	X	XXX
Nickel	XXX			x			XX	X		XXX	x		XXX
Silver		XXX			X			XX			XXX		XX
Titanium		XX		x	X			X		XX	x		XX
Vanadium		x			x	x	—	x	—	X	x	x	X
Zinc		XX			X			XX			XXX		XX
Kaolin	X ^d		XXX	X			x			XX			XX
Mica	x			x					x			x	x
Phosphate			x			x			—			x	x
Refractory clay			XXX						XX			XXX	XXX

^a Deposits are classified as laterite-saprolite, oxidized-enriched, and miscellaneous types; proportions are expressed as XXXX, more than three fourths; XXX, more than one half; XX, more than one fourth; X, more than one tenth; x, more than one hundredth; —, trace or occurrence.

^b Includes reserves, other identified and undiscovered deposits.

^c Bauxite is the only ore of Al in the western world, and the principal nonbauxite potential sources of Al are formed by processes other than weathering.

^d Both bauxite and kaolin are formed mainly by weathering, but some bauxite and large kaolin deposits have been transported.

most low-grade, oxidized, and leached zone; (2) the ore body containing supergene sulfides; and (3) an underlying low-grade unoxidized zone. In other deposits, such as some of the Fe ores, oxidation releases impurities, which occur mainly in carbonate and silicate forms, and the ore minerals are concentrated in residual accumulations. In this type of deposit, the ore occurs mainly in the upper parts of the rock below the low-grade surficial zones.

Miscellaneous Weathered Deposits

Several types of weathered mineral deposits cannot be appropriately assigned to either the laterite-saprolite or the oxidized and enriched groups. Most of these deposits accumulate in soils or nondescript earthy residues after other parts of the host rocks have been removed by weathering. The miscellaneous deposits include karst-type bauxite, phosphate, nodular manganese, some of the barite, several types of gem stones, and quartz crystals. Large refractory-clay deposits occurring below coal beds are grouped with these deposits for lack of a better classification. These clay deposits were once water-logged soils occurring under peat.

PRODUCTION AND RESOURCES

Deposits formed by weathering have been major sources of metals essential to the growth of the nation's industrialized economy, and production is continuing though domestic reserves of some ores are steadily being depleted. More than 3 billion tons of oxidized Fe ore have been produced in the Lake Superior region. Enormous tonnages of oxidized and enriched Cu ore have been produced in the Bingham Canyon district, Utah, and other districts in the western United States. All the domestic bauxite, the only currently economic ore of Al (except in the U.S.S.R.) is mined from deposits formed originally by weathering. The bauxite occurs in saprolite, earthy residual material, and material that has been transported. The only Ni currently mined in this country is in saprolite deposits at Riddle, Oregon. Considerable quantities of Ag are produced as a by-product of enriched Cu ore, and most of the Ga obtained domestically is a by-product of Arkansas bauxite. Other minerals and rocks produced from weathered deposits in the United States and the world are listed in Table 7.1.

The future is not bright for supplying our long-range needs for several essential minerals from domestic deposits formed by weathering, but many other countries have large resources. The reasons for the unfavorable outlook for domestic sources are that our resources were not nearly so large as those in tropical regions and that the many deposits we do possess have been depleted because they tend to occur near the surface and therefore were relatively easily found and mined. Known domestic bauxite resources, including currently subeconomic deposits, are sufficient to supply our needs (without imports) for only a few years. On the other hand, known laterite-type bauxite deposits in Australia, Guinea, Brazil, and other countries are so large that they can supply the world's needs beyond the next century; moreover, the prospects for significant new foreign discoveries are excellent. Most of our Mn is imported

from the Moanda district, Gabon. These deposits are the laterite type, and similar deposits are mined in Brazil and India. Large resources of manganiferous laterites occur in the countries mentioned and in other tropical countries. An estimated 80 percent of the world's resources of Ni are in laterite deposits (U.S. Bureau of Mines, 1979, p. 105). These resources are mainly in deposits that are now or will in the foreseeable future be mined in New Caledonia, the Dominican Republic, Australia, Indonesia (Island of Sulawesi), Guatemala, the Philippines, Columbia, and elsewhere. Many of the world's Precambrian Fe ores have been oxidized and enriched, and several of them may be ancient laterite deposits. The only young, surficial laterite-type Fe now mined is near Conakry, Guinea. Similar laterite Fe deposits occur in Cuba and Brazil, and large low-grade blankets are present in many tropical countries.

Minor production of metals from deposits formed by weathering include Co as a by-product from Ni in saprolite in New Caledonia and chromite from saprolite deposits in Brazil. Several minor elements occur in weathered rocks that are potentially recoverable as by-products of the principal metal. Among those in bauxite are Th, U, Be, La, Sc, Y, and P.

PRESENT LEVEL OF UNDERSTANDING

It is well known that the resistance of minerals to weathering ranges from salts that are dissolved with the first rain to resistant ones, such as zircon, that persist even in placer deposits. Many attempts have been made to establish orders of stability or resistance to weathering (Valeton, 1972). Such rankings are of help in understanding the general scheme of stability of minerals but have marked limitations influenced by different geologic factors and different conditions of weathering. Minor changes in the chemistry or physical conditions under which the processes are active, brought about by such things as variations in rainfall, climate, topography, and characteristics of the parent rock, cause major differences in the rate, effectiveness, and products of the processes.

The mobility of elements during chemical weathering ranges broadly because variable and commonly opposing factors interfere during stages of hydrolysis, solubilization, secondary mineral formation, and ion exchange in very fine-grained minerals (Lelong *et al.*, 1976). In temperate belts, the sequence of mobility of major elements commonly found is Ca, Na, Mg, K, Si, Al, and Fe in decreasing mobility. In tropical regions, release rates increase greatly, and it is difficult to identify the relative mobilities of the more effective elements. One of the principal reasons mobilities are difficult to classify is that elements occur in so many different soluble forms in weathering rocks. In solution, major elements occur as free ions (Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Fe^{2+} , Fe^{3+} , Al^{3+} , and others); in complex forms such as $\text{Mg}(\text{OH})^+$, $\text{Ca}(\text{OH})^+$, $\text{Al}(\text{OH})^{2+}$, and $\text{Al}(\text{OH})^{4-}$; and in organic complexes. Trace elements commonly are in the form of complex cations; for example, $(\text{UO}_2)^{2+}$ and $(\text{UO}_2)\text{OH}^+$. Many anions are present in natural solutions, including OH^- , SO_4^{2-} , HS^- , CO_3^{2-} , HCO_3^- , as well as complex anions of other elements.

The mobility of elements depends on the chemical compo-

sition of the solutions, especially the acidity (or alkalinity) and oxidation state (Hawkes and Webb, 1962). Solutions in most of the environments of weathering are within the pH range of 4–9, but within that range the concentrations of hydrogen ions vary by a factor of 100,000. Major differences in the behavior of hydrolytic reactions occur within this range of hydrogen ion concentrations. The strongest reducing conditions in weathering occur where all free oxygen is consumed by organic activity and carbonaceous matter is accumulating. Under a given set of pH and Eh conditions an ion of one oxidation state can be readily soluble, whereas a different ion may form insoluble compounds. Changes in Eh and pH conditions may change the relative solubilities of ions markedly, as is shown in phase diagrams (Figure 7.1) based on theoretical considerations and calculations. According to these diagrams, Al is leached and Fe enriched where pH and Eh conditions represented in area A (Figure 7.1A) exist and Al enriched and Fe leached under the conditions of area B.

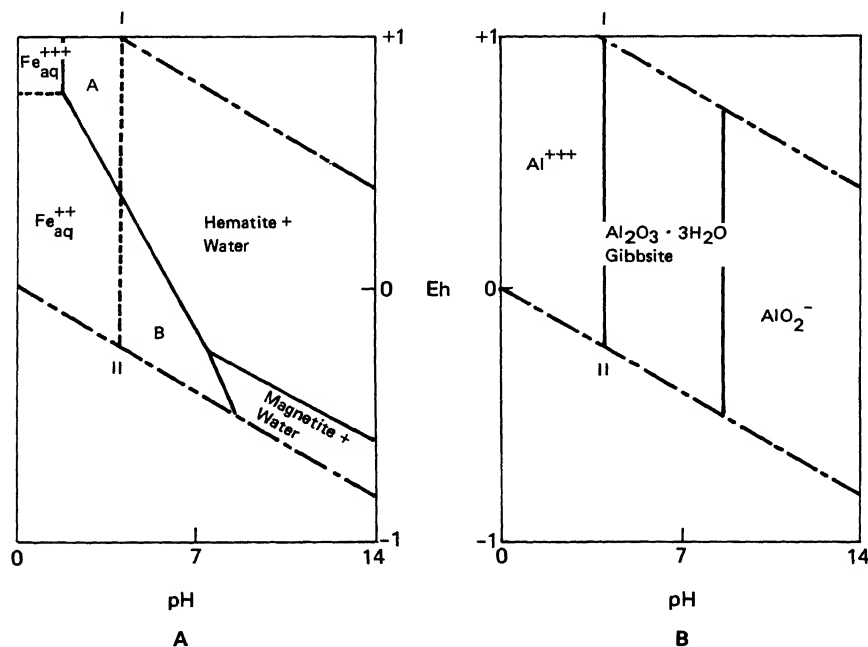
The processes of ion exchange and fixation (the movement of exchanged ions into tightly held positions) also are active in weathering. Ion exchange takes place in clay and other fine-grained minerals, and the capacity of the organic fractions of soils is particularly high (Hawkes and Webb, 1962). The exchange in minerals takes place where unsatisfied electric charges on the edges and within the layers are satisfied by loosely held ions that can be replaced by others introduced in solutions. Fixation takes place where minerals have relatively strong charge deficiencies and the ion introduced in the exchange process is bonded so strongly that it is virtually a part of the mineral structure.

Excellent work by Trescases (1975) on Ni laterite-saprolite deposits in New Caledonia made significant contributions to

the knowledge of the formation of this type of deposit. The deposits form on nickeliferous peridotites, and the complex concentrations of Ni are controlled by land forms, subsurface drainage, seasonal rainfall, and other factors. The largest deposits are on high plateaus, and other deposits occur in the slopes on the edges of plateaus and in swampy lowlands.

The more immobile elements during weathering of peridotite were found to be Fe, Co, Cr, and Ni; Fe is by far the least mobile. As the soluble elements (mainly Mg and Si) are hydrolized and leached, the peridotite alters irregularly to coarse-grained saprolite with many hard rock fragments remaining. In this stage Ni is trapped in partly altered serpentine and accumulates in newly formed asbolane (cryptocrystalline hydroxides of Mn, Co, Fe, and Ni), goethite, and nontronite. As the weathering front penetrates deeper, the saprolite becomes finer grained and the rock fragments are altered. Asbolane and goethite remain in the fine-grained saprolite, and the Ni present is mainly in these minerals. The Ni occurring in other forms is released chiefly during the leaching of Mg from serpentine under lowering pH conditions that are apparently caused by humic acids from decaying organic material. This Ni migrates downward and further enriches the coarse-grained saprolite altering from the fresh rock and thereby forms most of the Ni ore. Trapping of Ni takes place where water movement is restricted by the lower permeability of the fresh rock and the higher pH due to increasing release of Mg. A third type of enrichment takes place where Ni is introduced by lateral groundwater movement. Such concentrations occur where fracture zones and other structural feature are favorable for water movement, under the lower parts of high plateau surfaces that have a karstlike topography, on the edges of plateaus, and in lowland swamps. The transported Ni is trapped in inherited

FIGURE 7.1 Eh–pH diagrams at 25°C, A, Fe–water, line I–II is superimposed from B to show limit of alumina solubility; B, Al–water. Figure is modified after Petersen (1971), who lists appropriate sources.



Ni silicates (serpentine and chlorite) and weathering products of olivine (silica-ferrie gels and nontronite) in the upland saprolite and mainly in nontronite and garnierite in lowland swamp deposits. Iron being the least mobile element forms laterite crusts on the most weathered plateaus. Such crusts contain very little Ni, because absolanine is destroyed and goethite is converted to hematite.

The origin of extensive lateritic bauxite deposits formed by weathering in several tropical countries has been described by many geologists. Deposits tend to form in well-drained terrain in regions of heavy rainfall. Under such conditions, weathering is exceptionally active and is known to concentrate Al_2O_3 more than tenfold. The leaching process tends to remove alkalis, alkaline earths, and silica; Al, Fe, Ti, and several minor elements accumulate. Most of the Al in the earth's crust is in feldspar, and therefore this group of silicate minerals is the major parent of bauxite; however, many other minerals contribute Al. Several investigators have concluded that feldspar alters first to alumina-silicate gel or noncrystalline solid matter. These materials tend to form Al-silicate clay minerals (mainly endellite and kaolinite) that with further leaching of SiO_2 are transformed into the bauxite mineral gibbsite. Field relationships and ages of bauxite minerals indicate that gibbsite, $\text{Al}(\text{OH})_3$, alters to boehmite, $\text{AlO}(\text{OH})$ (a more-dense, stable, and harder mineral), with aging and dehydration at tropical temperatures. Boehmite, in turn, apparently alters with aging under surface or near-surface conditions to its denser polymorph, diaspore. This alteration sequence in bauxite minerals is indicated by (1) the dominance of gibbsite in young bauxite deposits including those still forming, (2) the abundance of boehmite particularly in the upper parts of deposits of mid-Tertiary age and throughout most deposits of Mesozoic age, and (3) the abundance of diaspore in deposits of Paleozoic age. The Fe in bauxite also tends to pass through a noncrystalline phase that changes to the hydrous oxide, goethite, and to the oxide, hematite, with aging.

Element mobilities and weathering phases in bauxite formation conform in a general way to diagrams of solubilities controlled by pH-Eh conditions, thermodynamic conditions, and reaction kinetics. The leaching of SiO_2 can take place in an acid environment as exists in tropical soils (Lelong *et al.*, 1976). Under intense leaching conditions, solubility limits of silicate minerals containing alkalis such as feldspar are reached before the limits for quartz. Such an explanation would account for quartz being present and all the other silicates being absent in a few bauxite deposits.

Temperature also may be important because thermodynamic calculations show that in acid systems an increasing temperature tends to reduce solubility of gibbsite and increase that of kaolinite. According to solubility diagrams (see Figure 7.1), Al is more soluble than Fe at low pH (less than 4) when the environment is sufficiently oxidizing. These conditions explain the Fe-rich surficial crusts overlying bauxite observed in several tropical areas. The results of field studies of bauxite formation to provide adequate information to test theoretical calculations and phase diagrams are not available.

Iron is removed during the formation of some bauxite deposits by complexing activity in which acid Fe-organic com-

pounds are formed or organic material causes the development of a low-Eh environment favoring the formation of Fe^{2+} and more soluble forms of Fe. The principal field evidence for such activity is that many of the valuable low-Fe bauxite deposits are associated with lignite or other organic material or have other characteristics indicating formation in a swampy environment. The low-Fe bauxite may contain less than 1 percent Fe_2O_3 , whereas the typical laterite-saprolite-type bauxite formed under oxidizing conditions in well-drained areas contains less than 15 percent of this oxide.

Though much remains to be learned about the complex chemistry involved, the origin of supergene-enriched porphyry Cu deposits is reasonably well understood (Blanchard, 1968; Swartz, 1966). Oxygen from the atmosphere, or dissolved oxygen in the water moving downward through rock, comes in contact with disseminated Cu and Fe sulfide minerals. The oxidation of these minerals forms sulfuric acid and Cu and Fe sulfates. If the acidity is not excessive, Cu is fixed as malachite, azurite, chrysocolla, and other oxidized minerals. Where this chemical environment prevails, some enriched Cu ore may form in the oxidized zone. In some deposits, carbonates or CO_2 concentrations are low and there is sufficient pyrite to provide abundant sulfuric acid to attack the Cu-bearing sulfides. The released Cu solution percolates downward. Under reducing conditions below the water table, Cu is precipitated as chalcocite and other Cu-rich sulfide minerals. Commonly these minerals replace other sulfides that are low or lacking in Cu. A typical porphyry Cu deposit is particularly favorable for Cu enrichment because the host rock has abundant fractures and joints allowing water and air movement, and its composition is such that acid groundwater is not readily neutralized by reaction with wall rocks.

PROSPECTING TECHNIQUES

The prospecting techniques applied in finding ore-grade metal concentrations in laterite-saprolite and other surficial minerals deposits involve the identification of weathering surfaces that have existed for a long time. This is done by applying geomorphology to locate old plateaus and stable uplands. Topographic maps, aerial photographs, and side-looking-radar imagery (where available) are extremely valuable in this step. Geophysical studies have proved to be of little help in locating bauxite, because the properties recorded are not sufficiently different from those of associated rock. However, some of the geophysical methods would be applicable in locating Fe, Mn, and Ni deposits associated with ultramafic rocks. In places, vegetation serves as a guide to favorable terrain for laterite deposits, because the intense leaching that formed the minerals removed plant nutrients, and the soil above deposits supports only dwarfed vegetation. In fact, some mineral deposits have been found by agricultural scientists investigating soil infertility.

A considerable amount of sampling and chemical analytical work are necessary in any exploration program. Samples are secured by hand augering and augering or drilling with several types of mechanized equipment. Because the ores in laterite-

saprolite deposits tend to be concentrated in veinlets and nodules and tend to consist of several different minerals, bulk samples from test pits or trenches are essential for beneficiation and metallurgical tests. One analytical method used in the field is simply the determination of weight loss as a function of temperature, because different ore minerals lose their hydroxyl water at different temperatures. Semimobile field laboratories having atomic absorption, photoelectric colorimeter, and heat-pressure-digestion systems for analysis are also in use. X-ray diffraction and emission analysis in permanent laboratories are used to support exploration programs.

Many deposits are concentrated in sink holes in carbonate rock, and therefore enclosed depressions are favorable places to search. Unusual red, dark brown, or black colored earthy material also may indicate favorable ground. Other physical properties, such as the high specific gravity of barite or the pisolitic texture of bauxite, also attract attention.

Exposures of leached cappings of oxidized and enriched deposits commonly attract attention because of their weathered cellular characteristics and abundance of red, yellow, and brown Fe oxide and hydroxide minerals. Those above sulfide deposits, called gossans, commonly contain recognizable textural evidence of pyrite and other sulfide minerals and have subsidence features (Blanchard, 1968). Secondary chalcocite and related sulfide minerals are typical of the enriched zone below the cappings.

The primary tool in the search for oxidized Fe ores is the airborne magnetometer, which detects the magnetic protore. Once favorable areas are located, detailed geologic mapping and ground magnetic surveys, possibly supplemented by gravity surveys, serve to outline targets for drilling.

GAPS IN KNOWLEDGE

Many shortcomings exist on the understanding of weathering as ore-forming processes. Among the principal reasons is the fact that most geologists, because of training and interest, do not recognize the abundance of challenging problems. Therefore, they concentrate on fresh rock and minerals, and they consider soil and weathered rock to be undesirable material that only obscures subjects of greater interest. Weathering processes also are not so attractive as other topics of research because the products are typically fine grained and contain may intergrown noncrystalline and poorly ordered phases. They are difficult to characterize even with such modern methods as x-ray diffraction, electron microscopy, and infrared and electron-probe analyses. Equipment of this type is not portable. Moreover, it cannot be used directly where weathering of rocks is in progress without disturbing natural environments, which results in gaps between experimental and field observations. On the other hand, the pressure-temperature environments of weathering are such that experimental equipment can be inexpensive and the reactions more easily observed than those of the magmatic and hydrothermal processes.

Especially difficult problems result from the tendency for the kinetic factors to dominate the thermodynamic ones and

in understanding and monitoring the processes in progress on minute scales. A few of the types of difficulties caused by these problems follow: (1) In some of the laboratory experiments on weathering, the first bauxite mineral formed is boehmite, and this mineral later changes to gibbsite. Ample field evidence and geological associations indicate that gibbsite forms in the early stages of weathering and later alters to boehmite. (2) Eh or pH measurements in the field are made with probes in saturated ground, and it is extremely difficult to obtain meaningful reproducible results. The Eh or pH of the water surrounding the probe may be quite different from that of the molecular layers of water surrounding the mineral being altered by weathering. (3) The roles of organic complexing and bacteria activity have been established in the laboratory, but observations and measurements of their activity and products in nature are still problematical. For example, Oborn and Hem (1961) established in experiments that bacteria can influence the movement of Fe and other elements. This and other research support the conclusion that bacteria are important in weathering, but how they contribute to the formation of several types of ore deposits in nature remains little better than weakly supported theory. Among the reasons are that the complexities of natural environments cannot be duplicated in the laboratory and even a short interval of geologic time cannot be repeated in experiments.

Still other problems concerned with shortcomings in knowledge about some types of weathering are rooted in geography and the competitive nature of industry. Part of the reason for the inadequate studies of weathering processes in North America is that they are most active and, therefore, can best be studied in the tropics, which are remote from our academic and government research centers. Most North American geologists working with tropical laterite-saprolite ores are in industry. The company geologist who has both the time and facilities to study the scientific aspects of ore formed by weathering is rare, and permission to publish his findings is even rarer. Perhaps the latter factor is why so many of the advances in studies of laterites have come from eastern Europe, particularly Hungary and the U.S.S.R. The U.S.S.R. has had active teams prospecting for bauxite in several developing countries recently. In the Republic of Guinea, which recently increased its annual bauxite production to more than 10 million tons, an output surpassed only by Australia and Jamaica, Soviet geologists are on the staff of the national university and the U.S.S.R. is sponsoring a new mining engineering school. In 1978 this school had 25 Soviet geologists and mining engineers on its staff. A second point not to be overlooked is that geologists in western Europe, particularly in France, which still has possession or heritage ties to several countries in the tropics, have made numerous contributions to the knowledge of weathering that are not widely known in the United States.

SUGGESTED FIELDS OF RESEARCH

A great deal of research and synthesizing of knowledge is needed, and many projects could contribute to the understanding of

weathering as ore-forming processes. However, the projects that will prove most successful in blunting the mineral supply problems that hover beyond the horizon pertain to a better understanding of the occurrences and improved prospecting methods for finding new deposits. Possible programs that might lead to discoveries include the following:

1. Improved methods are needed for locating valuable deposits in the United States that are under and obscured by extensive blankets of surficial materials. Buried deposits formed in the past and probably still being altered or eroded by circulating subsurface water undoubtedly will be found in some of the following regions: (a) areas covered by pediment gravels making up more than one half of the extensive and productive Basin and Range mineral province in the southwestern United States; (b) much of Washington, Oregon, northern California, and Idaho covered by lava flows; (c) most of the north central states and southern Canada covered by glacial drift; and (d) the Piedmont region extending from New Jersey to Alabama that is blanketed by thoroughly weathered rocks.

One logical way of approaching the problem of finding buried deposits in the four regions is to develop a multidisciplinary task force containing expertise in the fields of geomorphology, geochemistry, geophysics, hydrology, geochemical prospecting, economic geology, and structural geology. In the early stages of the study, the bedrock surfaces underlying the blanketing materials in the first three regions and the interface of the hard parent rock and the weathered saprolite in the Piedmont region should be investigated thoroughly and mapped where practical. The geomorphology, hydrology, and geophysics expertise would probably contribute most in this stage. The next step would be to outline target areas for mineral deposits along these surfaces and interfaces. The selection of targets should include the analysis of all logical projections of structural features, lineaments, and intrusive and possible other lithologic boundaries into the blanketed regions (and the study of water chemistry and shallow and even deep circulating waters where practical) that may be of help in locating concealed deposits.

Probably the task force would conclude that hydrogeochemical prospecting is one of the best methods for searching for obscured targets for mineral deposits. This method would be particularly applicable to deposits still being oxidized and leached, either in stages of formation or destruction, and therefore apt to have geochemical halos of dissolved trace metals (Beus and Grigorian, 1975). The covering of large regions by such a prospecting program would require the analyses of thousands of water samples from springs and wells and would be a huge task. It might be approached in two ways. One, which is the smaller and therefore has the better prospects for funding, would be two or three small projects focusing on limited favorable areas. The second would be a joint effort with agencies now analyzing water and encouraging them to submit samples to central laboratories for complete analyses. Groundwater sampling should be given priority; surface water in selected regions should also be examined. Such a program could yield a great deal of information of value in finding concealed mineral

deposits and, in addition, contribute data necessary in dealing with water quality and supply concerns.

2. Considerable work is needed to provide adequate knowledge of paleoclimatology and the possibilities of finding more mineral deposits formed by weathering of ancient land surface preserved in the geologic record. Deposits formed during paleoweathering intervals in the United States and their ages include refractory clay (Pennsylvanian and Cretaceous), bauxite (Eocene, Miocene), and kaolin (Cenozoic). Bauxites that originated mainly by weathering are widespread in Late Paleozoic, Mesozoic, and Cenozoic rocks in several countries. A thorough study of paleoweathering surfaces and paleoclimatology presumably in the context of former crustal plate configurations, pole positions, and ocean currents would outline areas to prospect for several types of deposits.

3. Several research projects might be proposed for the purposes of contributing to the background of scientific knowledge needed to understand fully the formation of mineral deposits by weathering, and a few projects have potential of producing new information of value in mineral prospecting. Particularly needed are coordinated experimental and field investigations such as the study of element release, mobility, fixation, and other aspects of weathering of a single rock type as well as several different rock types under varying climatic and other factors influencing weathering. Adequate studies of this type would require that observations be made in tropical areas where weathering is exceptionally active. Field researchers should also live and work in the study area sufficiently long to monitor the effects of seasonal climatic changes and periods of uncommonly heavy rainfall and drought.

The island of Hawaii would be an excellent place for a thorough study of weathering because rocks having similar compositions occur where the many factors influencing weathering have near maximum ranges. For example, environments for plant growth vary from tropical rain forest to virtually alpine, and, in addition, part of the island is extremely dry much of the year. Such things as rock porosity and permeability, slope, land forms, and relative age of exposed rock have comparable ranges of variations, and there are seasonal changes in rainfall, temperature, and plant growth.

The place recommended for studying variations of varied rock types supported by U.S. research funds is Puerto Rico. Limestone, serpentinite, and several varieties of volcanic rock are being weathered under similar climate here, providing a necessary complement to the Hawaiian study. Some of the volcanic rocks contain porphyry Cu deposits that have definite economic potential, and information on their behavior during weathering would be useful in finding similar deposits elsewhere.

A thorough study is desirable of the nickeliferous laterite-saprolite in California and Oregon of the type Trescases (1975) completed in New Caledonia.

Investigations are needed of the roles of bacteria and organic matter and their influences of pH and Eh conditions during the formation of ore. Presumably work of this type would be

done if the studies for Hawaii and Puerto Rico were active, but work on these subjects in several mining districts could also yield information on how ore is formed by weathering.

4. Research projects leading to the improvement of conventional methods or developing new approaches for rapid prospecting of large regions could be fruitful. Such methods might be successful in parts of the United States but would more likely help in large virgin regions such as the Guyana shield and parts of the Amazon Basin in South America and remote parts of Africa. Possible research topics might be more rapid method applications of conventional geochemical methods, the development of new geophysical-chemical ore finders such as the *in situ* neutron-activation methods, and improvements in geophysical and remote-sensing methods. Furthermore, remote sensing of vegetation might indicate metals without chemical sampling of each soil, thereby providing a rapid, wide-ranging method of selecting favorable ground.

Weathered materials have provided much of our resource base in the past and will continue to do so in the future. However, if the United States is to rely on its own resources, a resurgence of effort will be needed, both theoretical and applied.

RESEARCH PERSPECTIVE

Advancement of knowledge of weathering will aid in understanding how, and in what geologic environments, several types of ores form and how mineral deposits within the reach of weathering are eventually dissipated. The understanding of the processes will, in turn, provide a basis for recognizing rocks formed or altered in environments favorable for ore formation and thereby aid in identifying exploration targets.

Improved knowledge of weathering will unquestionably aid in the search for domestic mineral deposits; however, the greatest application will be in developing countries in tropical regions. Laterite-saprolite deposits in tropical regions contain most of the world's current economic Al and Ni and much of its Mn resources, and the United States will continue to be dependent on them.

The best prospects for contributing to the discovery of domestic mineral deposits are advances leading to improved methods of finding ores under the extensive covering blankets in the four regions discussed in the previous section. Based on the information now available, the most likely possibility for finding deposits of sufficient size to help blunt future supply problems are the oxidized and enriched porphyry Cu type in the southwestern part of the United States, for it is generally recognized that large deposits remain to be found in this region.

Paths of research that will certainly bear fruit are coordinated field and laboratory efforts that apply the predictive capability of theoretical studies to the principal task of interpreting natural environments. Such studies can provide information on how during weathering elements are (1) released and migrate, (2) concentrated by additive processes or by removal of contaminants, and (3) apparently so greatly influenced in their mobility

by subtle environmental variations. Such knowledge will provide a basis for understanding the complex chemistry of oxidation and enrichment of heavy metals. It can lead to advances such as the explanation of why some laterites are rich in Al and others in Ni, Mn, or Fe and improved capabilities in recognizing a particularly favorable geologic environment.

Finally, geochemical prospecting in general will benefit from an improved knowledge of what happens to elements released from, or captured by, ores during various stages of attack by weathering.

Though many calculations of solution rates and stabilities of Al, Fe, Mn, Ni, and other elements have been made (Garrels and Christ, 1965; Norton, 1973; Petersen, 1971; and many others), much remains to be learned in this field before an adequate understanding of the origins of ores by weathering is achieved. Undoubtedly, present ideas will be modified with future improvements in thermodynamic data and knowledge of kinetics, role of organic complexing, and metastable equilibria.

The enrichment of porphyry Cu deposits and other sulfide ores by supergene processes has been studied by many researchers, but several gaps in knowledge remain. Details of the complex chemical reactions in the near-surface environment are not understood. Another debatable point is whether the reducing environment in which deposits are enriched is just above or below the water table.

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Research in Sedimentation as an Ore-Forming Process

8

RICHARD P. SHELDON *and* OMER B. RAUP
U. S. Geological Survey

INTRODUCTION

Sedimentary minerals form an important class of ore deposits, which includes among others, most of the world's Fe ores, phosphate, and potash. These deposits are formed at the boundary between the solid earth and the hydrosphere (oceans, lakes, swamps, or rivers) by the chemical processes of precipitation (through evaporation or changes in concentrations, acidity or alkalinity, or redox potential), replacement of (or adsorption on) pre-existing minerals, or by the physical process of winnowing to form placers.

Sedimentary minerals, particularly the young deposits, are formed by processes that can be observed directly in nature or can be duplicated in the laboratory, and their formation is much better understood than those mineral deposits formed at depth in the earth. Thus, conceptual models of the origin of some sedimentary minerals tend to be relatively well defined, and exploration techniques, therefore, tend to be effective.

Much remains to be learned, however, of the mechanisms of formation of sedimentary minerals. The prospects are excellent for the discovery of many more sedimentary ore deposits by applying new knowledge of the formational processes. For

example, processes occurring in the deep ocean are difficult to observe and are chemically complex. Because these processes are not well understood, we have found it difficult to assess deep-sea resources.

The rapid expansion of knowledge of mineral origin and exploration technology has been instrumental in the discovery over the last few decades of deposits of Fe, phosphate, potash, zeolites, and barite. Increased perception of the behavior of metals under near-surface conditions has resulted in the identification of large, low-grade deposits in deep-sea muds and black organic-rich shales. Discoveries of low-grade deposits are of great interest, because sedimentary deposits generally follow the rule that the lower the grade, the larger the size, both in total tonnage and in total valuable minerals. Thus, sedimentary mineral deposits will become increasingly important in the future as other classes of deposits with less-favorable distribution habits are depleted.

CLASSIFICATION

Sedimentary mineral deposits can be classified according to their environment of deposition. They are defined here

TABLE 8.1 Classification of Sedimentary Mineral Deposits by Environment of Deposition

Geologic Environment	Physical-Chemical Environment			Process of Deposition
	Normal	Euxinic	Evaporitic	
Marine				
Deep sea	Mn nodules (Mn, Co, Ni, Cu), Barite			Precipitation; adsorption
Midocean ridge and graben	Metalliferous muds			Precipitation
Continental shelf	Phosphate, zeolites	Phosphate, black shale (containing V, U, F, and rare earths)		Precipitation, adsorption, replacement, winnowing
Restricted basin	Fe, Mn	Black shales (containing U), Fe	Halite, gypsum, potash	Precipitation
Beach	Placers (heavy minerals)			Winnowing
Nonmarine				
Swamp and lagoon	Fe, clay, phosphate			Precipitation, adsorption
Lake			Salts of Na, Mg, Li, B, Al, K, zeolites	Precipitation, replacement
River	Placers (heavy minerals)			Winnowing

geologic and physical-chemical parameters, giving a binary classification and noting the process of formation (Table 8.1).

Many other classification schemes are possible (Gableman, 1976) and have value for specific purposes. However, because resources research and exploration are guided primarily by genetic principles, a genetic classification based on the environment in which the sedimentary mineral formed may be more suitable than one based on rock type, emplacement mechanism, host lithology, host rock reactivity, and source of elements.

The two basic categories of sedimentary environments, non-marine and marine, are divisible into local geographic (paleogeographic) environments (Table 8.1), each of which may be classified according to its physical-chemical environment. The hydrous physical-chemical environments most relevant to mineral deposits are of (1) "normal" chemical composition (e.g., they fall within normal ranges of salinity and oxygen content for the general ocean environment at that period of geologic history), (2) euxinic, and (3) evaporitic. A third dimension of classification is added by noting the process of deposition for each of the binary classes above, e.g., precipitation, adsorption, replacement, or winnowing.

All sedimentary mineral deposits of importance to this study are classified according to this scheme (Table 8.1). Sedimentary materials that are abundant and used in large quantities, such as building stone, sand and gravel, road metal, and cement rock, are excluded because development requires little scientific leverage. Moreover, they are generally not commodities of world trade.

The commodities treated in this study are listed in Table 8.2, which also gives the order of magnitude of their contribution to present and future usage. It is clear that sedimentary mineral deposits are at present important to society and will become increasingly so in the future.

TABLE 8.2 Sedimentary Mineral Commodities and Their Relative Importance to Total World Production

Commodity	Present	Future
Metals		
Iron	High	High
Uranium in phosphorite	Low	Moderate
Vanadium	Low	Moderate
Rare earth elements	None	Moderate
Manganese	None	High
Cobalt	None	High
Nickel	None	High
Copper	None	Moderate
Other manganese	High	High
Copper	High	High
Zinc	High	High
Aluminum in dawsonite	None	?
Uranium		
Platinum		
Zirconium		
Gold		
Rare earth elements		
Tin		
Titanium		
Nonmetals		
Fluorine in phosphorite	Low	Moderate
Zeolites	High	High
Phosphate	High	High
Potash	High	High
Barite	High	High
Boron	High	High
Gypsum	High	High
Halite	High	High
Other sodium minerals	High	High
Lithium	High	High

PRESENT LEVEL OF UNDERSTANDING

The general state of knowledge of each of the classes of sedimentary mineral deposits is presented to focus later on the gaps in that knowledge and the opportunities for further research.

NORMAL MARINE ENVIRONMENT

Beach Placers

Heavy minerals of many types are being and have been concentrated in beach deposits. These minerals arrive at the beach by stream transport or by wave erosion and transport. Notable examples of economic beach placers include diamonds in South Africa; gold in Alaska; ilmenite, rutile, and monazite in India; and rutile, ilmenite, and zircon in Australia.

Exploration techniques can be tailored to the physical and chemical properties of the heavy resistant minerals of beach-placer deposits. Various geophysical techniques will detect unusual concentrations of heavy minerals if they are not too deeply buried.

Normal Shallow Sea and Restricted Basin Deposits

Iron-rich sediments form the major economic mineral deposits found in this environment. The oxidized Fe facies were deposited in oxidized waters, whereas the reduced facies were deposited in an euxinic environment. The Fe in these deposits of Phanerozoic age was derived mostly from chemical weathering of rocks exposed on the continents and carried by acidic, reducing streams to the ocean, which in Phanerozoic times were generally alkaline and oxidizing. When these waters were mixed, the Fe precipitated to form Fe-rich shallow marine and lagoonal sediments such as the Clinton Fe ores of Silurian age in the eastern United States (Sheldon, 1970).

The majority of economic Fe deposits, however, are not Phanerozoic but are the banded-Fe formations of Precambrian age that are found on all continents except Antarctica. The origin of the banded-Fe formations is somewhat obscure, but they apparently were deposited mainly in shallow, continental seas (see James and Sims, 1973). Thus their environment of deposition is comparable with that of the Fe-rich sediments of the Phanerozoic; the deposition, worldwide, of unusually large amounts of Fe-rich sediment possibly signals the transition in the evolution of the atmosphere-hydrosphere from reducing to oxidizing condition (Garrels and Mackenzie, 1971). The source of the Fe, whether from weathering of rocks or a suboceanic, volcanic source, remains a subject of dispute. The lack of understanding all aspects of their genesis is not critical for prospecting because the abnormal magnetism, high specific gravity, and large size of deposits allow rapid and effective exploration by aerial remote-sensing surveys. The world's Fe resources are sufficient to last almost indefinitely into the future, and the future supplies of Fe are clearly more dependent on mineral extraction research than on resource and exploration research. However, a better understanding of Precambrian sedimenta-

tion of all minerals must take into account the origin of the banded-Fe formations.

The normal shallow-sea-restricted-basin environment has also served as the site of stratabound base-metal sulfide deposits, many of which are thought to be syngenetic and to have formed at normal temperatures at the earth's surface. Such deposits are found in a wide range of geologic environments from ancient deep-ocean sediments to modern peat bogs. Others, like the Kuroko deposits of Miocene age in Japan, were formed by volcanic emanations at elevated temperatures.

The African Copperbelt of Precambrian age in Zambia and Zaire is perhaps the best known example of a stratabound Cu deposit that is regarded as syngenetic by most geologists familiar with the field relationships (see, for example, Chapter 6; Garlick, 1961; Vink, 1972). A zonal mineral sequence ranging from chalcocite through bornite and chalcopyrite to pyrite extends seaward from the strand line in the lowest marine transgressive unit that overlies nonmarine, locally eolian sandstones.

Other deposits that have at least superficial similarities to African Copperbelt deposits include the Kupferschiefer deposits of Permian age in central Europe, the Flowerpot shale of Permian age in Oklahoma and Texas, the Udokan Cu deposit of Precambrian age in eastern Siberia, the Cu deposits in the Revett Formation of Precambrian age in western Montana, and the Adelaidean System Cu deposits in South Australia.

No currently forming Cu deposits have been recognized that are analogous in size or grade to the ancient ones described above. However, small, much lower-grade occurrences of metal-rich muds have been reported in association with modern volcanic island arcs. These warrant further study in an effort to understand the origin and distribution of the older deposits.

Continental Shelf Deposits

The large economic phosphate deposits were formed in shallow seas on the continental shelves adjacent to major ocean basins (McKelvey, 1967; Cook, 1976). Phosphate deposits on the present-day continental shelves are found only at latitudes less than about 40°. Most are found in the trade-wind belt on the west coast of northwest and southwest Africa, southwest North America, and northwest South America. Here, upwelling ocean currents, such as the Humbolt Current off the west coast of South America or the Benguela Current off the west coast of South Africa, bring nutrient-rich, deep-ocean water to upper levels of the ocean (Riley and Chester, 1971). This sets off a complex chain reaction of oceanographic and sedimentologic events, including deposition of phosphatic sediments, by a combination of precipitation, replacement, and winnowing and accompanied by incorporation of minor metallic elements in the phosphate mineral by precipitation and adsorption. The final phosphate sediment is a carbonate fluorapatite with replacements in the apatite structure or by adsorption on apatite crystallites of U, Co, rare earths, and other trace elements. Tertiary rocks of marine origin adjacent to such areas of seafloor deposits commonly contain similar sedimentary rocks, and paleogeographic and paleo-oceanographic reconstructions show that many ancient rocks belonging to the same environmental province also contain similar deposits of phosphate rock (Shel-

on, 1964). Associated with these deposits are black, organic-rich, and commonly metalliferous shales; biogenic chert; and carbonate rock with fossils of open-ocean organisms such as planktonic foraminifera.

Not all phosphate deposits have these rock type associations. Exceptions include some important deposits, such as the Rajasthan deposit of India (Banerjee, 1971) and the Florida and North Carolina deposits of the United States (Cathcart, 1968; Riggs, 1979). The Florida and North Carolina deposits were formed at low latitudes but were not the result of strong upwelling ocean waters. Their deposition may have been associated in one way or another with the Gulf Stream or a countercurrent to it (Gibson, 1967), but it is not clearly understood.

Other mineral deposits that form in the continental shelf marine environment are sedimentary zeolites. These zeolites, such as clinoptilolite, are aluminosilicate minerals of the alkalis and alkaline earths that have unique properties that make them technologically useful. In the agricultural and animal husbandry industries, they are used as soil amendments, dietary supplements for poultry and swine, deodorant and desiccator for animal wastes, and purifying agents for recirculating hatchery waters in aquaculture. Other industrial utilization of natural zeolites includes the production of high-purity oxygen from air, removal of water and carbon dioxide from sour natural gas, purification of methane from decaying garbage in landfills, removal of ammonia from sewage, and preparation of catalysts for hydrocarbon conversions. Other technological opportunities for utilization of natural zeolites clearly exist.

Major deposits of zeolites occur in continental shelf sediments and are exemplified by deposits in Japan (Utada, 1970; Iijima and Utada, 1972). When fine-grained volcanic ash is deposited on the shelf or on land and subsequently is washed onto the continental shelf by streams, chemical alteration in the marine environment transforms the ash into zeolite minerals. Shelf sediments in Japan contain deposits that are many meters thick and widely distributed.

Mid-ocean Ridge and Graben Deposits

Manganiferous muds have recently been found in low areas in the mid-Atlantic ridge and graben system (Rona *et al.*, 1976) and associated with margins of the Nazca plate in the Pacific (Field *et al.*, 1976). The Mn seems to be associated with the leaching of basalt by heated seawater at divergent plate boundaries. The resulting subsea thermal springs mix with normal seawater, causing the precipitation of relatively pure manganiferous oxides. Manganese deposits of this origin are represented in the geologic record in what were formerly known as eugeoclinal deposits but are now recognized to be seafloor sediments accumulated in a large pile at convergent plate boundaries.

Deep-Sea Deposits

Metal-rich nodules on the floor of deep-ocean basins consist of nodules ranging in size from a few millimeters to several tens of centimeters. Some areas contain so many nodules that they touch one another to make a continuous pavement (Horn *et*

al., 1976). In one area of about 2600 square kilometers, the nodules contain an average of more than 25 percent Mn, 1.0 percent Cu, 1.0 percent Ni, and 0.25 percent Co; other metals are also present. Iron occurs in substantial amounts, but it probably would not be economically recoverable. Preliminary exploration indicates large tonnages of nodules on the ocean floor. Dredging of the nodules from great depths and extraction of the metals from the nodules will require development of innovative mining and metallurgical technology (Dorr *et al.*, 1973).

Some ancient marine sedimentary rocks have been interpreted to have been deposited in a deep-sea environment. Rocks of this type in Nevada contain commercial deposits of barite, which is used in large volumes in oil-well drilling fluids. Although there is considerable scientific uncertainty as to the mode of formation of these deposits, it is thought that the Ba was most likely discharged from submarine springs and reacted with sulfate in the seawater to form barite. The association of the barite with sedimentary rocks of deep-sea origin furnishes the geologist with a set of criteria that can be used in the search for mineral deposits elsewhere in the world (Shawe *et al.*, 1969).

MARINE EUXINIC ENVIRONMENT

Euxinic (reducing and sulfide-rich) conditions occur in two marine geographic environments:

1. On the continental shelf at depths corresponding to the free-oxygen-minimum layer of the ocean water column, which is at present in the interval from about 400 to 800 m below sea level
2. In restricted basins along the ocean edge.

Continental Shelf Deposits

Black shales are associated with phosphate rocks deposited in normal marine environments. Some black shales as well as significant amounts of the phosphate rock are deposited in the euxinic marine environment. The phosphate mineral is stable in an alkaline-reducing environment, whereas black shale is stable in an acid environment. The separation of the black shale and the phosphorite facies is through variations in pH (Sheldon, 1963, pp. 146–147). The metal content of both the black shale and the phosphorite is high, so that both constitute a small current by-product source of V and U and a potential source of many other metals including Co, Ni, and rare earths.

Restricted Basin Deposits

Iron-rich sediments were formed in the normal-marine, restricted-basin, and ocean-edge environments. Such environments commonly alternate between oxidizing and reducing, thereby profoundly affecting the sedimentary-Fe facies. In the euxinic environment the Fe-rich sediments contain Fe carbonate, ferrous silicates, Fe sulfides, and perhaps magnetite.

Black shales that are rich in U and other trace metals have been deposited in widespread, broadly restricted, epiconti-

nental seas (Vine and Tourtelot, 1969). They include such deposits as the Chattanooga shale and its correlative in the United States and the kolm-bearing Alum shale of Scandinavia. Those sediments are generally relatively thin. They are differentiated from adjacent rocks by their color and abnormal radioactivity and can be readily discerned in gamma-ray logs of boreholes.

MARINE EVAPORITIC ENVIRONMENT

Evaporites may form in several geologic environments; however, those that contain deposits of commercial interest were formed in restricted basins.

Restricted Basin Deposits

Extensive and thick evaporite deposits formed in basins that were marginal to oceans. The flow of seawater into and from these basins was restricted so that evaporation was able to play a major role in the concentration of salts. Where only minor amounts of stream-transported materials entered the basins, the sediments that accumulated were chemical precipitates of relatively high purity. Under ideal conditions the materials deposited, through a range of increasing salinity, are limestone, dolomite, gypsum (and anhydrite), halite, and finally the extremely soluble salts of K and Mg. The evaporite minerals of major economic importance are gypsum, halite, and sylvite or carnallite.

Halite, gypsum, and anhydrite are widely distributed. Halite, unlike gypsum and anhydrite, generally is not preserved at the earth's surface because of its high solubility. Rocks representing the final stages of evaporation must be located by regional geologic analysis and tested for their halite content by drilling. Halite has been sought throughout the entire history of man. The mining of salt is a major industry, as it is used as a primary material in a vast array of chemical products. Despite its rarity as a surficial rock, halite resources are tremendous. Unfortunately, the potassic and magnesian products of extreme desiccation are much less abundant.

Sylvite, the least common of the industrial marine evaporite minerals, is essential as a major component in fertilizer. Although sylvite is commonly associated with halite, it is much more restricted in its distribution, and, therefore, more sophisticated techniques are necessary to find it.

Residual brines that remain trapped in evaporite basins and in sedimentary rocks adjacent to them contain valuable dissolved materials, particularly K, Mg, Br, and Li.

NONMARINE ENVIRONMENT

Swamp and Lagoon Deposits

Except for coal, minerals deposited in swamp and lagoon environments have relatively small economic value. They include bog Fe-ore deposits, which have been extensively mined in the past but are of little economic value in the United States

today. Phosphate is deposited in estuarine environments, and large kaolin deposits accumulated in swamps and lagoons. The phosphate deposits are small and generally have relatively high contents of Fe and alumina, which decreases their value as a fertilizer raw material.

Extensive coal and humate deposits are formed in the swamp and saltwater marsh environment. These deposits are locally enriched in a variety of elements such as U, V, and Zn, which in some coals are valuable by-products. However, such concentrations are clearly diagenetic, and ore deposits of this origin are treated in Chapter 6 of this study.

Lake Deposits

Saline lakes contain a wide variety of evaporite minerals. Halite and potassium salts are being recovered from lake waters by evaporation in ponds marginal to Great Salt Lake, Utah. Trona (sodium carbonate) is being mined from Eocene lake beds of the Green River Formation in Wyoming. Borate minerals have been mined for many years from Tertiary lake beds in Death Valley, and B and Li are recovered from subsurface brines at Searles Lake, California.

Zeolites are abundant in saline-lake beds (Surdam and Sheppard, 1978). Volcanic ash deposited in these lakes was altered from its original glassy material to zeolite minerals by the lake brines. Large deposits of zeolites are widely distributed throughout nonmarine basin deposits of the western United States (Sheppard, 1971).

The solubility of Li salts is so high that Li remains in the residual brine even after most of the common salt has been precipitated by evaporative concentration. Brines and volcanic ash-rich sediments from saline lakes may also contain economic concentrations of Li as at Clayton Valley, Nevada. Most Li today is used in the aluminum and glass industries, but in the future large quantities may be required for new types of batteries, heat exchangers, and thermonuclear (fusion) power reactors.

River Deposits

Rivers and streams produce the most important type of placer deposits; these have yielded great quantities of Au, Pt, Sn, diamonds, and other precious stones. Stream placers are one of the earliest types of mineral deposits discovered and worked by man, and the techniques for their discovery and exploitation have been developed to a high degree. This, combined with the easy accessibility of such deposits, has probably resulted in the discovery of most of the important geologically recent placer deposits.

Ancient placer deposits present more of a technological challenge in that their discovery requires geologic analysis, sophisticated exploration techniques, and usually costly drilling. Ancient detrital deposits, such as the huge Witwatersrand Au and U deposits, are probably placer deposits, although many aspects of their origin are in dispute. The offshore tin deposits of Malaysia also include fossil placers formed when sea level was lower.

INADEQUACY OF PRESENT PROSPECTING TECHNIQUES

The primary scientific philosophy influencing past exploration technology for sedimentary minerals has been the dictum that "the present is the key to the past," one of the principles on which geology was founded. The philosophy has served us well and will continue to be the guiding rationale for continued study of modern geologic environments, undertaken for the purpose of developing additional new principles.

However, the present may not be typical of the past in many important respects, and insofar as this is true our prospecting techniques for ancient deposits will not be effective. This is particularly true for processes such as sedimentation, weathering, and erosion. The composition of the atmosphere and hydrosphere of the Precambrian era was profoundly different from the present composition (Garrels and Mackenzie, 1971). Much of the difference was brought about by the appearance and evolution of life. The atmosphere contained little or no oxygen early in the earth's history, so that minerals such as pyrite and uraninite that are easily oxidized but are otherwise highly resistant to chemical or physical destruction occur as heavy minerals in ancient placer deposits. The production by plants of free oxygen at the expense of carbon dioxide made the hydrosphere oxidizing and increased the pH to the point that the oceans became alkaline, so that minerals such as calcite, apatite, gypsum, and ferric oxide became chemically stable in the marine environment. The evolution of organisms that used minerals to form their hard parts, which were subsequently incorporated into sediments, caused profound changes in the composition of the oceans. For example, the early ocean was probably saturated with respect to opaline silica, but with the evolution of silica-secreting organisms, the oceans became undersaturated, thus changing the sedimentation habitat of silica. This, combined with the changes in the oxidation state of the oceans, resulted in the cessation of deposition of banded-Fe formation in Phanerozoic time and the appearance of the Clinton-type Fe deposit in which chert is absent.

Much is to be learned about the evolution of the atmosphere, hydrosphere, and lithosphere. Their effects on the formation of sedimentary ore deposits are unknown but probably large. The development of this knowledge will allow the development of new exploration technology, resulting in the discovery of new mineral deposits. In the following section some gaps in knowledge are identified, and the technological opportunities of research aimed at those gaps are assessed.

TECHNOLOGICAL OPPORTUNITIES

The development of sedimentary mineral resources has been highly responsive to research efforts. That is, new ideas of the occurrence and distribution of sedimentary minerals as well as new geophysical or geochemical exploration techniques set off new waves of effective exploration. It has been observed by some mineral economists that advances in technology of *exploitation* of mineral deposits have great leverage for increased production because the new technology applies to known as

well as undiscovered deposits. They have contrasted this with what they considered a lesser leverage of advances in technology of *exploration* of mineral deposits. They reason that exploration adds only a few deposits at a time. Their point is debatable because a new exploration concept applies worldwide and can be as effective in discovery of obscure deposits in known districts as in virgin areas. It can be said that to a new exploration concept the earth is unexplored, so that the leverage of research in exploration is comparable with that of research in exploitation.

Research on the geology of sedimentary mineral deposits can produce technological opportunities for development of resources of a number of important commodities. These include phosphate rock, potash, zeolites, Li, ancient placer U, and deep-sea nodules, which are treated individually in detail below. In addition, research in the geologic history of the earth can produce technological opportunity for development of resources of ancient sedimentary minerals in general. This includes research in evolutionary trends in the atmosphere and ocean, paleoclimate, paleo-oceanography, paleogeography, plate tectonics, and cyclicity in major geologic processes. These are also discussed in detail below.

PHOSPHATE

Although much research has been applied to the genesis of sedimentary phosphorite, the problem is complex enough and the data are sparse enough to allow multiple genetic interpretations for even the better-known deposits. These differing hypotheses of origin lead to differing exploration strategies, at least some of which must be in error; so it is important that definitive research be accomplished. A recent workshop (Burnett and Sheldon, 1979) examined these research opportunities and heavily contributes to the following discussion.

The geochemical cycle of phosphorous—from the petrology of igneous apatite through the weathering and transportation phases to sedimentation—needs better definition. Particularly important is more precise consideration of mass balance of the cycle as it is related to the geochemistry of phosphate in the hydrosphere and lithosphere.

The mineralogy and geochemistry of sedimentary apatite are not fully understood in terms of defining the range of natural compositions and mineral structures and the chemical processes of formation. Further laboratory research on these subjects is needed.

Stratigraphic and sedimentologic research on at least four phosphate-bearing regimens needs to be continued in order to derive more accurate sedimentologic models from them. These include the Miocene rocks of southern California, the Permian rocks of the Rocky Mountains, the Tertiary rocks of the Atlantic Coast, and the Precambrian phosphorite and related rocks in Rajasthan, India.

Phosphatic sediments have been found on the seafloor, largely in areas of upwelling near the coast, as the result of widespread bottom sampling from all oceans. This environment should be studied in detail to better understand the controls and character of the sedimentation of phosphatic and related sediments. The best opportunities for study are the continental shelves of Mex-

ico, Peru, and southwestern Africa. Studies of other marine sedimentary environments, such as the Atlantic shelf of the United States, the Bass Strait of Australia, the Chatham Rise of New Zealand, and selected seamounts in the tropical northwestern Pacific Ocean could contribute to an understanding of the conditions under which phosphorites such as the Miocene and Pliocene deposits of the southeastern United States were formed. A number of the existing hypotheses of origin could be tested and sharpened by such marine sediment studies.

Finally, marine phosphate sedimentation should be quantitatively modeled using data from ancient rock studies and supported by laboratory and marine geologic studies to develop a better predictive capability for use in phosphate prospecting.

Studies of the fate of weathering products of phosphorite and their occurrence in groundwater should be carried out. These include fluorine, helium, and perhaps trace metals.

POTASH

Potash is concentrated in saline waters and deposited as evaporite minerals; its origin is no mystery. However, the processes of chemical sedimentation are imperfectly understood, particularly with respect to basin fluid dynamics and geochemical processes attending surficial evaporation. Three kinds of modeling studies are needed to enlarge the geologic understanding of the basinal distribution of potash deposits. First, geologic facies studies of rocks containing potash need to be carried out to develop conceptual sedimentation models based on real deposits. Second, these conceptual models should be tested by computer modeling. Finally, scale modeling should be carried out in arid areas to test the results of the first two modeling studies.

The use of Br geochemistry is a promising geochemical method for potash exploration (Raup and Hite, 1978). Bromine is incorporated through solid solution into halite as it is precipitated in an evaporite basin. The amount of Br in the halite appears to be proportional to the Br content in the brines from which it precipitated. Because Br is concentrated in the brine through an evaporation cycle and through a period of increasing salinity, the Br in the halite also increases. By determining the amount of Br in halite rocks, it is possible to reconstruct the history of hypersalinity in an evaporite basin (Raup *et al.*, 1970). From experience it is known that when the Br content reaches approximately 250 parts per million in the halite, potash minerals begin to precipitate. By analyzing enough halite samples in a basin, it is possible to determine if and where potash may be present. A recent major potash discovery was made in Thailand using this method (Hite, 1974, 1977).

Reconstruction of the salinity history of an evaporite basin can also be used to indicate depositional sites for other rock types associated with the evaporites. In the Paradox Basin, Utah, Hite (1970) was able to show that algal carbonate rocks were deposited on the edge of the basin in response to specific changes in basin salinity. These rocks are now reservoirs for petroleum.

More information is needed on the details of Br geochemistry in evaporite basins, and we need to know more in general about the mechanisms of evaporite formation.

ZEOLITES

The genesis of zeolites in sedimentary rocks is understood in general terms; however, several problems merit additional study. Phillipsite and clinoptilolite are the chief zeolites in young deep-sea deposits, but the relative importance of the precursor materials and the interstitial fluids in their formation are unknown. Tuffs of originally rhyolitic composition in deposits of alkaline, saline lakes characteristically yield a variety of zeolite minerals, but the factors that control which particular zeolite forms are poorly understood (Sheppard and Gude, 1973). Low-temperature experimental studies, combined with studies of the zeolites and associated interstitial fluids in Holocene tuffs currently undergoing alteration, may provide some answers. Another problem that warrants investigation is the relationship of the chemistry of a certain zeolite species to the geologic setting of the host rock.

Other areas of research of a technological nature that deserve consideration are (1) development of techniques for the separation of zeolites from the gangue, (2) development of techniques for the separation of one zeolite from another, and (3) chemical or structural modifications of natural zeolites to increase their usefulness (Sheppard, 1973). Natural zeolites or zeolitic rocks will undoubtedly be used in many industrial and agricultural processes; however, additional applied research is necessary to achieve these goals.

LITHIUM

Major future resources of Li will probably come from brines or sediments in saline lakes. Determination of the source of Li in the lakes would be a key to establishing successful exploration techniques. Likely possibilities are (1) that the Li was leached from subsurface rocks by deep groundwater circulation, which was stimulated by subsurface heat and volcanic activity, and (2) that the Li was introduced to the lakes by near-surface leaching of volcanogenic rocks (Vine, 1976). When discharged into a lake that has no outlet, Li may become concentrated by evaporation to form a Li-rich brine or react with saline waters and shallow sediments (especially those containing volcanic ash) to form Li-bearing minerals such as hectorite, $\text{Na}_{0.33}(\text{Mg}, \text{Li})_3\text{Si}_4\text{O}_{10}(\text{F}, \text{OH})_2$. Additional Li resources may be discovered by locating lake basins that contain brines and determining if the brines or associated sediments are rich in Li (Vine and Brenner-Tourtlot, 1977). Lithium isotope ratios may be useful in distinguishing thermal source areas. Exploration targets may be narrowed by using existing geophysical techniques such as gravity, direct current resistivity, and electromagnetics to locate the presence of, or the depth to, subsurface brines and salt bodies (Smith and Mabey, 1976). Remote-sensing techniques may also be useful in recognizing thermal areas and in distinguishing playa surfaces of different textures and mineralogy. Evaluation of drillholes might be aided by development of new downhole probes, such as a specific ion detector that is sensitive to Li or a Li detector that would take advantage of the high neutron-absorption profile of Li.

URANIUM IN PLACERS

Beds of quartz-pebble conglomerate that were deposited in the deltas of ancient rivers are a major source of U, Au, and potentially Th (Finch *et al.*, 1973). They have been estimated to contain 17–59 percent of the western world's reserves of U (the wide range being the result of different assumptions regarding the future price of U and different guesses regarding geologic uncertainties), and they have yielded approximately 55 percent of the Au produced from all sources throughout history.

One hypothesis on the origin of these ancient deposits is that the Au, U, and Th minerals were deposited as heavy mineral concentrates in placer deposits. Gold and certain Th minerals are common constituents of modern placers, but U minerals are not. The U oxide minerals that characterize ancient quartz-pebble conglomerates are highly soluble in oxygen-bearing waters and are rarely encountered as detrital minerals in modern river sediments. Yet they occur as rounded grains along with abundant, commonly well-rounded, sand- and pebble-sized grains of pyrite and of other readily oxidizable minerals in the ancient conglomerates. It is hypothesized that they must be restricted to conglomerates deposited early in the earth's history, before green plants had released much free oxygen to the atmosphere by photosynthesis. This change in the earth's atmosphere, from little free oxygen to abundant free oxygen, may have occurred approximately 2300 million years ago, and, if so, U ore of placer origin would be expected only in quartz-pebble conglomerates more ancient than this. Research is needed to further develop and confirm this important hypothesis.

The United States has no proven reserves of either U or Au in ancient quartz-pebble conglomerate, but since 1975 radioactive quartz-pebble conglomerate of appropriate age has been discovered at three localities in the western states (Black Hills, South Dakota; Medicine Bow Mountains, Wyoming; and Sierra Madre, Wyoming—Hills, 1977; Miller *et al.*, 1977; Graff and Houston, 1977). The potential for discovering economic deposits of U, Th, or Au in one or more of these areas or in adjoining areas, where the same tectonic setting occurs, seems to be good.

DEEP-SEA NODULES

The recovery of deep-sea nodules and their metallurgical processing should simply be a matter of engineering technology, provided that we know where they are and which areas are most metal rich. The solutions to these problems would be greatly facilitated if the geologic mechanisms of their formation were better known. Fortunately, the advent of new sophisticated oceanographic techniques, such as deep-water television cameras, powerful new light sources, and shipboard rapid chemical analysis systems, makes studies of the distribution and composition of these nodules possible. These developments will improve our chances for understanding how the nodules got where they are and where economic concentrations are likely to be found.

BASE-METAL SULFIDE DEPOSITS

An understanding of the environment of deposition of base-metal sulfide deposits in sedimentary rock and the zonal arrangement of the ore minerals would make possible the prediction of favorable areas in which to search for new deposits. Having once located an anomalous concentration of metal it may be possible to predict further the direction for finding valuable ore.

Many of the largest deposits of high-grade sedimentary copper ore occur in rocks of Precambrian age where first-cycle transgressive marine rocks overlie nonmarine rocks. If gypsum or other evaporites are present, the base-metal sulfide deposits commonly are found in the lower part of the marine sequence, below the evaporites. In some known Cu deposits, the position of the strandline and the Cu-bearing mineral assemblage is known, and the mineralogy changes seaward from chalcocite to bornite to chalcopyrite and finally to pyrite (Garlick and Fleischer, 1972). On empirical grounds, one should look in similar geologic environments in the search for new Cu deposits; however, additional research to develop the theoretical rationale for the observed habitats of sedimentary Cu deposits should greatly improve this exploration tool.

Phanerozoic rocks also have a significant potential, especially where the depositional environment changes from nonmarine to marine and where the rock sequence includes marine organic-rich shales and evaporites overlying nonmarine rocks. Prospective targets include the basal marine black shales and siltstone in a transgressive marine sequence and the base of evaporite sequences where either of these overlie a significant thickness of arkosic sandstone. Examples can be found among the many basins of Mesozoic evaporites that formed along the zone of rifting between Africa and the American continents. As in the case of Precambrian deposits, additional research is necessary to improve the theoretical basis for the distribution (Cox *et al.*, 1973).

GEOLOGIC HISTORY

In the last two decades, the science of geology has made two giant advances—the development of the theory of plate tectonics and the perfection of isotopic geochemical techniques for accurately dating many different kinds of rocks. Many other advances with lesser impact have been made, and taken altogether, the science of geology is in a golden age of exponential knowledge increase, whose end is not yet perceived. For example, the present doubling rate of North American university geology departments, numbers of geologists, and geologic literature is about 20 years. This scientific growth has had a profound effect on our understanding of mineral deposits and has lighted the way for further scientific advance. However, many questions remain.

A fuller understanding of the evolution of the chemistry of the atmosphere and ocean since the origin of the earth will give clues to the presence of the types of sedimentary ores deposited in environments that existed only during certain stages in the earth's history. The limiting of the search for

specific types of ore to rocks of a certain age span would be of great aid in exploration.

Evidence is accumulating that a periodicity of oceanic circulation and ocean depth may have been superposed over the evolving evolutionary trends (Fischer and Arthur, 1977). Development of knowledge of such periodicity would further limit the search for many kinds of ore deposits.

The changing of the positions of the continents and the effects of these changes on the extent, latitudes, and circulation of oceans have had great impact on the distribution of marine sedimentary mineral deposits. Development of better plate tectonic reconstructions, particularly in Paleozoic and earlier times, will stimulate the search for sedimentary minerals.

Finally, the development of the theory and history of paleoclimatic change in relation to the continents would also greatly stimulate the search for those sedimentary minerals whose genesis are affected by climate.

It is critical to further mineral resource development that such basic geologic research be continued.

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III

FUTURE MINERAL-RESOURCE STRATEGIES

Strategies for Research on Ore Deposits

9

LAWRENCE M. CATHLES III
The Pennsylvania State University

INTRODUCTION

The previous chapters in this study have reviewed the status of our scientific understanding of mineral deposits and have suggested specific research needed to clarify problem areas. Research in other areas of science has demonstrated that co-operative multidisciplinary efforts result in advances that are far greater than an equal amount of individual effort. The purpose of this chapter is to suggest a strategy for implementing integrated research approaches over several decades that could greatly improve our geologic understanding of ore deposits and our ability to explore for them effectively. As a prelude to discussing such research strategies, aspects of our resource problem will be examined briefly.

THE RESOURCE PROBLEM

One aspect of the resource problem is our need for dependable mineral supplies. Most experts recognize that total self-sufficiency is probably not realistic. Mineral deposits are geologic

rarities and occur with a geologic distribution that does not correspond to national boundaries.

Figure 9.1 shows, dramatically, that the United States began to lose its dominant position in world mineral production in the mid-1940's. In 1946 the United States produced 46 percent of the world supply; in 1978 it produced only 11 percent. During the same period, U.S. consumption of minerals increased, as did its dependence on foreign supplies. This decrease in self-sufficiency reflects the fact that international production has tremendously increased and the fact that the best deposits in the world are not necessarily found in the United States. Thus, U.S. mineral production has more foreign competition for domestic sales, for example, for many commodities for which there are proven domestic deposits, foreign sources can fill the demands less expensively—importation in these cases is an economic decision. Dependence on foreign sources is not intrinsically disadvantageous from either the U.S. point of view or that of the many resource-based and less-developed countries from which the United States obtains raw materials. However, in light of the possibilities of countries forming cartels and the unpredictable nature of international political patterns, the United States should take maximum advantage of its

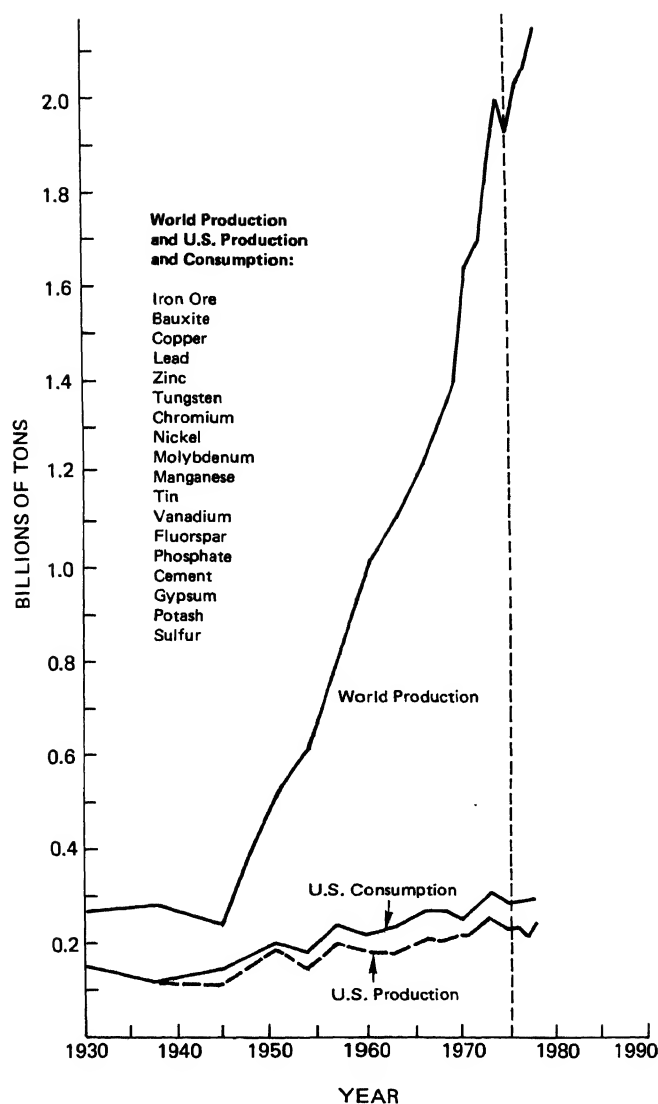


FIGURE 9.1 U.S. production and consumption compared with world production for 18 nonfuel minerals. The shape of the curve is not critically dependent on the particular minerals chosen. [Figure from Cameron (1973) with permission from the University of Wisconsin Press and the Board of Regents of the University of Wisconsin System.]

resource endowment and be as self-sufficient in raw materials as possible.

There has been a large and steady increase in total world production of minerals. Extrapolating this trend (Figure 9.1) there is a clear indication that new deposits must be discovered and brought into production on a continuing basis. Conservation and recycling of materials can help, but new deposits are clearly required, particularly if the entire world is to continue to industrialize. However, as Bailly (Chapter 1) and others have pointed out, the longer exploration is carried out in a given area, the more difficult and expensive discovery be-

comes. For example, most of western Europe has been explored for centuries; the discovery rate there is now small.

The mineral industry is characterized by wide swings in supply and demand, leading to alternating periods of shortage and oversupply. In the present conditions of moderate oversupply, the U.S. mining industry is having difficulty competing with foreign production, which often has the advantages of higher grade ore, lower cost, and more supportive governmental attitudes.

The resource problem, then, is really the question of what the United States can or should do to help assure the discovery of the mineral resources required to supply future needs that are certain to arise and to maintain appropriate resource self-sufficiency and independence.

WHAT CAN THE UNITED STATES DO?

The answer provided implicitly or explicitly to the above question both by the previous chapters and other experts at conferences addressing the resource problem is that the United States should use the next years to increase its geologic knowledge of ore deposits and develop and refine its exploration technology so that it is in a better position to find new resources more efficiently as needed.

Among the requirements for improving the discovery rate is the development of a regional geologic and geophysical data base. Regional geologic and geophysical mapping is clearly important and is far from complete in the United States; in fact, it lags behind many less-developed countries with regard to geologic, gravity, and aeromagnetic mapping. This lack was recognized in the report of the Pennsylvania State University workshop (Rose *et al.*, 1976), which recommended a major increase in the geologic, geophysical, and geochemical mapping budgets of state and federal surveys.

In addition to the building of regional geologic and geophysical data bases, we need to be able to interpret these and other data in terms of the likelihood of occurrence of ore. Previous chapters have indicated that this link is provided by mineral-occurrence models. These models may be simply empirical collections of geologic features commonly associated with mineralization; alternatively, they may have a broader theoretical or generic basis. Another way to increase exploration effectiveness is, therefore, to refine or develop better mineral-occurrence models.

The previous chapters have suggested that the features that constitute mineral-occurrence models can be subdivided into two groups: (1) those that identify geologic time intervals or broad crustal regions where exploration efforts can be most effectively focused and (2) those that identify specific local geologic factors necessary or favorable for the formation of an ore deposit. The ability to identify optimum intervals of geologic time or space would increase exploration effectiveness by directing effort to those strata and localities where discoveries are most probable. It would also improve our ability to estimate resource abundance and could provide more objective criteria for federal-land-use classification. Identifying specific necessary or favorable local geologic factors is the basis of exploration,

ment in this skill would increase exploration efficiency directly.

Needs of time or space criteria are noted in Table 9.1. For example, it has been recognized that the large increase in oxygen content of the atmosphere about 2 billion years ago is a major factor in changes in types of ore deposits being formed. Petersen (Chapter 3) point out that subtle changes in geochemistry may be reflected in trace-element abundances in black shale. If this relationship also holds for ore deposits formed in the ocean, it could lead to time-window criteria. They point out, for example, that the ratio of oxygen in the oceans was greater in the Cambrian than in the present. This difference is reflected in diagenetic ore deposits, which are a valuable guide to exploration.

Hydrothermal deposits—especially those formed by magmas as discussed by Burnham and Ohmoto (Chapter 4)—are spatially related to subduction zones. However, our understanding of these relations has many gaps. Not all subduction zones are equal, and we do not understand what causes different types of deposits to be formed instead of others. Paleogeographic reconstructions in the southwestern United States, British Columbia, and western South America have particularly rich examples of porphyry copper and molybdenum deposits. Examples in Japan have copper deposits, but they are smaller, higher-grade, massive sulfide, Kuroko type—very different from the porphyries of America but in some ways of the same metals. Adding to the puzzle, the deposits of Japan were formed in a narrow time interval about 1 billion years ago, even though there has been subduction in Japan for about 200 million years. Java appears to have neither Kuroko-type nor porphyry deposits despite subduction of the Indian Plate. If we could explain these differences, useful guidelines for exploration and prediction could result.

The past configuration of continents and oceans is another potentially valuable concept. The patterns of ocean circulation and climate can now be computed given past configuration of ocean, shelf, and continent. For example, a recent calculation for the Late Cretaceous by the Geophysical Fluid Dynamics Laboratory at Princeton shows unusually strong oceanic upwelling in the area of Saudi Arabia. This could have sustained a large biomass and may have facilitated the formation of major oil resources in that area. Precipitation patterns, climate, ocean currents, and subduction can be intimately related to formation of ore deposits, as previous chapters have shown. One has to be enthusiastic about the general, regional insights that we can gain from plate-tectonic reconstruction and calculation of past climate and ocean circulation. Comparison of these calculations with geologic observations will result in new kinds of exploration opportunities.

The question of which regions are most likely to contain significant ore deposits passes continuously into the question of local geologic controls, and they both share the problem of ambiguity. Critical factors (see Table 9.2 for examples) are often difficult to isolate because they may occur at some distance from ore and because several factors may overlap, thereby making the selection of the critical ones ambiguous. For example, the local setting of the Viburnum lead belt in Missouri includes the following: (1) ore is in dolomitized limestone, not far from the limestone-dolomite interface; (2) it occurs above pinchouts of the underlying LaMotte sandstone regional aquifer against basement highs; (3) the ore is spatially related to a reef complex; and (4) solution collapse and brecciation localize ore deposition. Which (or even all) of these features are critical to ore formation and location is difficult to prove; thus, the designation of critical features, whether local or regional, is a matter of individual interpretation.

Previous chapters have suggested quantitative process mod-

TABLE 9.1 Examples of Time and Space Restrictions That Could Assist in Directing Exploration to Areas Where Discoveries Are Most Probable

Event	Deposit
Evolution of the oceans and atmosphere	Uraninite placers prior to 2.3 b.y. Extensive iron formation 2.5–1.9 b.y. ago
Evolution of lithosphere	Komatiitic volcanism with nickel deposits, marked decrease since the Archean Laterite formation and preservation most prevalent since early Tertiary
Middle Proterozoic unconformity	Uranium deposits
Crust overlying subduction zones	Porphyry copper ores; hydrothermal veins
Continental rifting	Marine evaporites; carbonatites; fluorite deposits
Regional unconformities with paleokarst	Carbonate lead–zinc ores
Favorable continental configuration	Phosphate near upwelling ocean waters Laterites near tropics Continental evaporites in closed basins
Margins of craton near geosynclinal basins	Carbonate lead–zinc ores
Archean basins adjacent to mafic-rich sediment sources	Rand-type gold ores
Caldera complexes, especially following the latest stages of volcanism	Base-precious metal-bearing veins

TABLE 9.2 Examples of Local Factors That Can Guide Exploration

Local Factor	Deposit Type
Nickel-bearing magma interacting with sulfur-rich sediments	Magmatic nickel sulfides
Boiling of hydrothermal fluids, as noted in fluid inclusions	Epithermal vein deposits, silver + gold and base metals
Fluorine-rich rhyolites	Porphyry molybdenum ores
Uranium-bearing source rocks plus localized reductants	Sandstone uranium deposits
Paleokarst aquifer system	Carbonate lead–zinc ores
Concentric propylitic and sericitic alteration halos around a potassic altered core	Porphyry copper ores
Silicic submarine lava domes	Volcanogenic massive sulfide deposits
Increasing bromine–chlorine ratios in halite	Potassium-rich evaporites
Accessory hornblende in intrusives and Iron-rich skarns	Hydrothermal desposits

eling (Table 9.3) coupled with field studies as an aid to defining local ore-deposit controls. This parallels a general consensus among economic geologists. A recent opinion survey (Eidel, 1980) by the Society of Economic Geologists found that field–laboratory integrated studies and mineral-occurrence model formulation had the highest scientific priorities among exploration, research, and teaching geoscientists. The Pennsylvania State University Workshop on Research Frontiers in Exploration (Rose *et al.*, 1976) emphasized that the study of the regional controls of ore deposits has been relatively neglected compared with studies of the ore deposits themselves and proposed that ore deposits be cooperatively studied in a regional context. *A strategy for increasing our knowledge of local factors controlling ore genesis, and thereby increasing exploration effectiveness, is, therefore, to study and attempt to model quantitatively the ore-forming processes of individual deposit systems.*

The examination of larger regions than encompassed by local studies (that stop where the mines stop) could (1) distinguish the incidental from the critical factors responsible for ore formation and (2) recognize more-widespread, more-subtle clues to mineralization. Valid genetic studies must attempt to encompass, or at least define, the “whole system” responsible for ore formation. The system may extend a few kilometers in some cases, as for example, across a mafic intrusion, or it may extend

for hundreds of kilometers, as for example, across an evaporite basin, a paleoaquifer system, or a region of phosphate deposition. The investigations would be designed to define the sources of the ore elements, the processes of concentrating or dispersing them, the distinctive attributes that resulted in formation of ore, and the geologic, geochemical, and geophysical signatures associated with the mineralizing system.

Collaboration between industry, academia, and government is both mutually advantageous and vital. Industry participation at the grass-roots level would be essential because industry has the most intimate knowledge of the mineral deposits and controls access to those deposits. Academia and government have the pool of skilled individuals that can devote time to projects whose payoff may be many years in the future. Government should be interested and involved because it has a long-term commitment and responsibility for the problem of resource definition and availability, and it can provide the funds for such studies. An example of a large-scale research effort is the highly successful, nearly completed, Japanese–Canadian–American cooperative study of the Kuroko massive sulfide deposits of Akita, Japan, by about 30 scientists from universities, industry, and government.

Cooperative multidisciplinary studies of specific deposit types, with effort perhaps being coordinated by a small technical staff and a rudimentary field laboratory has many advantages: (1)

TABLE 9.3 Typical Process—Modeling Activities That, in Conjunction with Field Studies, Could Help to Better Define Local Controls on Ore Deposit Genesis

Process Modeling	Typical Application
Magma convection and crystallization	Ultramafic nickel, copper, chromite, vanadium, platinum-group metals
Hydrogen escape from intrusive	Porphyry copper; chromite
Fluid–rock interaction	Wallrock alteration; laterites; hydrothermal ore deposits
Basin hydrology	Carbonate-hosted lead–zinc
Evaporative fractionation	Sandstone–uranium
Convective fluid circulation	Potash deposition
	Hydrothermal ores of many types

The effort would be applied to a relatively neglected scale of study. (2) Genetic concepts resulting from the research would be directly relevant to exploration. (3) The studies would provide an institutional structure that would naturally coordinate geologic, experimental, and theoretical work. (4) The nature of the project would, in itself, foster industry-academic-government collaboration. (5) A field station with a lifetime of 5-10 years would provide enough time to address problems that are longer term than the usual doctoral thesis. The studies may include many basic research projects, however, that could be the subject of doctoral theses. (6) The study areas would provide a locale to test new ideas, tools, and techniques. (7) The attempts to model the ore-forming processes quantitatively would force consideration of the proper tough questions such as the overall chemical mass balance of ore-deposit systems.

Choices of mineral systems to be studied could initially be selected from each of the classes discussed in the previous chapters—magmatic, hydrothermal, sedimentary, diagenetic, and weathering. In each case, a staff of at least one coordinator, a secretary, and at least one assistant would be needed to man the field station and coordinate research by at least 10 professionals—much as a chief mine geologist would, but on a more regional scale. A tie-in with an existing academic, industrial, or governmental research facility would be beneficial for library, shop, and laboratory support. Periodically, the status of the project should be reassessed and a decision made to continue, broaden, or redirect effort. Ten years is probably the maximum tenure of study of a single system.

The last topic we need to consider is the level of effort required. Each regional study would probably require between \$1 million and \$3 million per year. Thus, roughly \$5 million to \$15 million per year would be required for the regional studies of the five classes of mineral systems mentioned above. The total figure is small compared with the amount spent of exploration each year and thus fulfills the criterion that the expenditures have substantial leverage (see Table 9.4). Our aim is to increase exploration effectiveness with an expenditure small compared with that spent on exploration itself. The cost

is also significantly smaller than present U.S. government (the National Science Foundation and the U.S. Geological Survey) expenditures in the mineral resource area (see Overview). The most important factor, however, is not the yearly dollar value of the expenditure but rather its steadiness over the next 20 years. We should seek steady progress and not expect dramatic breakthroughs in mineral-exploration effectiveness. A commitment of steady funding is required if progress is to be made.

The specific nature of the overall support and guidance of such research activities is beyond the purview of this panel, which was to identify the broad scientific needs, whereas the specific planning and implementation requires administrative and fiscal policy decisions. Perhaps a board of governors representing industry, academia, and government could coordinate planning and funding through interaction with those federal agencies concerned with nonfuel minerals.

SUMMARY

We identify the nonfuel resource problem as being the maintenance of an adequate future discovery rate and appropriate resource self-sufficiency. A reasonable plan is to start now and with steady purposeful funding attempt to avoid or ameliorate potential shortages by increasing future exploration effectiveness through research. We have discussed various ways that this might be done and have identified studies in diverse areas (Tables 9.1, 9.2, and 9.3) that could have useful impact. We have identified a specific approach to increase geologic exploration effectiveness through multidisciplinary studies of particular deposit systems. A modest increase in the present levels of funding could support this new and promising dimension in research. If we start now along the proposed path, significant increases in exploration effectiveness can probably be achieved in 20 years. Two caveats should be mentioned: First, 5 years have already elapsed without progress since similar proposals were made at the Pennsylvania State University Workshop. We need to start soon, if we are to have an impact on potential

TABLE 9.4 Approximate Expenditures for Exploration-Related Activities in Government and Industry Compared with Cost of Proposal Made in Text

Cost of new proposals	
Cost of Regional Studies	
5 @ \$1 million to \$3 million =	\$5 million to \$15 million/yr
Private exploration expenditures	
Dollar value of nonfuel, noncommon building materials consumed in United States in 1978 to support a gross national product of \$2 trillion	
	\$20,000 million
Exploration expenditures for these materials (2% of \$20,000 million)	\$400 million
Government expenditures	
Present level (FY 79) of government expenditure (USGS and NSF only) in nonfuel resource-related earth sciences research	
	\$31 million

future mineral shortages. Second, the research program outlined can have positive impact on U.S. resource self-sufficiency only if the U.S. mining industry is a viable industry 20 years from now. For this to be the case, government must maintain a climate in which a mineral industry can survive and flourish. Substantial prospective federal lands must remain open for exploration and potential mineral exploitation; environmental regulations must not foreclose the opportunity to develop new deposits.

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Toward Improved Understanding of Mineral Resources—Critical Needs in Education, Training, and Transfer of Information

RICHARD H. JAHNS
Stanford University

INTRODUCTION

aid that human productivity in the fields of mining, agriculture, and fishing serves as the tap root for our tree of civilization. Yields from these activities are net additions to the wealth of the world which the world must struggle to maintain its standard of living. Yet there are fundamental limitations: the ready availability of most mineral resources, a declining standard of living that has not been receiving the widespread attention that is needed to forestall some serious problems in the future.

For many mineral commodities produced and consumed in a given area of the civilized world, three successive stages of development can be considered. The first, or "enough here" stage, is characterized by an abundance of known deposits, and hence a high ratio of supply to demand. The United States has been fortunate than many other countries in having entered this stage for a substantial number of commodities. But increasing demands and concomitant diminution or exhaustion of available domestic supplies, "enough here" gradually gives way to a second, "enough somewhere" stage in which the domestic supplies are augmented from

foreign sources. This is the current situation for many mineral commodities used in the United States.

In terms of present technology, we can anticipate a third stage—"not enough anywhere." Many thoughtful investigators have accepted this notion, although there is considerable disagreement about timing of the third stage, or immediate threat of such a stage, for most mineral commodities. Certainly the timing can be expected to shift according to changes in discovery rates, techniques of extraction, patterns of use, economic and social trends, and other factors.

More than a quarter of a century ago, a rather grim future for many domestic mineral supplies was suggested in the widely distributed "Paley Report" (President's Material Policy Commission, 1952). The analyses in that report have proved to be remarkably accurate under the test of subsequent time (see, e.g., Brobst and Pratt, 1973; U.S. Bureau of Mines, 1975), but until recent years they have been largely ignored by policymakers and the general public. Concerns about serious shortages of petroleum, not yet representing the "not enough anywhere" stage, have tended to preoccupy most people, and it also has been claimed by some that a crisis stage need not be reached for most mineral commodities. Typical arguments are

that world reserves of most minerals may well be much higher than generally estimated, that the recycling of metals and other materials is not given adequate attention, that assumed rates of growth in demands for mineral resources are excessive, and that variable substitutions of readily obtainable materials can be made for some of those in short supply (e.g., Meadows *et al.*, 1972).

In a response to such claims, scientists at Columbia University (Tien *et al.*, 1976) conclude that "the mineral resource picture remains grim. We have refuted each major criticism of previous depletion analyses by analyzing depletion rates under a low growth rate with an unrealistically large figure for global reserves, by including possible large-scale recycling, and by showing that exponential growth is real and not some hypothetical gremlin invented by seekers of doom. We have even allowed for mining of soil and found it to be plagued with energy and environmental problems. Yet, simple calculations have shown that even with all these hypothetical changes in the global system, the conclusion is still that depletion of certain economically essential minerals is not far off, even if a little less imminent." They go on to note that "the industrial machine has an extremely large appetite for minerals worldwide. Over two trillion dollars are spent yearly on minerals . . . and necessary changes we must make in a wasteful yet demanding society . . . will come to pass only if we succeed in radically revising our social values and developing an awareness of the importance of conservation and recycling."

Among the several analyses of future trends—some of them are broad but most of them highly detailed—there is little general agreement as to the rates of depletion or the timing of practical exhaustion of mineral resources. But there is much agreement as to reality of the trends, with a general anticipation of potential problems for many commodities within the next half-century, as pointed out elsewhere in this volume.

Discussions in the foregoing chapters indicate some exciting avenues of inquiry for improving our basic knowledge of needed resources and for determining how they can best be discovered. We can expect significant improvements in our understanding of mineral occurrences, in patterns of mineral use, in effectiveness of substitutions, and in negotiated trade-offs among mining activities, environmental considerations, and other competing factors. But will these improvements come soon enough to forestall or mitigate major crises, severe social and economic stresses, and perhaps even drastically imposed changes in life-styles during the coming half-century?

Clearly there is urgent need for thoughtful policies and careful decision-making, for we can afford neither inaction nor serious mistakes if we are to spare future generations a spate of critical problems. Here the important matters of lead time and effective trade-offs are particularly worrisome. The lead time required for most worthwhile programs and projects cannot be shortened, even in the face of crises, without formidable costs. And it must be acknowledged that effective trade-offs among competing interests will remain uncommon until policies, regulations, and decisions reflect balanced consideration of the entire systems that are involved. For development of a systemic view, for establishment of a truly effective resources policy,

and for intelligent decision-making well in advance of crisis situations, we need both increased knowledge and vastly improved means for transfer of knowledge among cognizant people. In this, our educational system is of prime importance.

TECHNICAL TRAINING FOR TECHNICAL CAREERS

Toward providing the expertise and nourishing the attitudes necessary for solution of mineral-resource problems, our educational system must continue to identify and attract able young minds and to stimulate them toward careers in the geosciences and mineral industries in the context of high-quality training. It is fair to ask how we have been doing on this score.

About 30 college-level institutions in the United States can be identified with significant programs of education directly pertinent in one or more ways to the field of mineral resources. Most of these institutions have been active for a century or more, and the pertinent programs have existed in many of them for time periods nearly as long. During the past three decades, however, efforts in these programs have shown varying levels of popularity among students. The upward and downward shifts have not always been closely correlated with fluctuations in demand for well-trained graduates. In 1955, for example, there were 30 accredited departments of mining engineering in this country, a number that dropped to 21 by 1965. A further drop to 16 occurred by 1972, and this number persisted through 1978 as student enrollments increased markedly (Society of Mining Engineers, 1979). An encouraging development during the past few years has been the organization of several new programs and the successful resuscitation of at least two defunct ones. Related areas, including mineral engineering, mineral processing, geologic and geophysical engineering, and economic geology, also have been favored in recent years by upward trends in the number of viable programs, number and quality of faculty staffing, and student enrollments.

College and university enrollments in curricula directly related to the mineral industries essentially doubled in this country during the period 1974–1978, reaching a level of about 4500 in 1977–1978. The recent output of graduates in mining engineering has been about 350 annually, and in 1976 approximately 730 degrees were awarded to graduates of programs in this and related engineering, geologic, and geophysical fields. Slightly more than one quarter of the total represented advanced degrees. About 1000 college entrants each year now express interests in mineral-resources training, a most encouraging development. Indeed, the recent trends may be approaching consonance with projected needs in the mining industry for the coming decade, even though it seems likely that such consonance will not be fully reached during that time. The 1977 Mineral Industry Survey of the American Mining Congress, for example, yielded an estimate of at least 4000 new mining engineers to be required by mining companies during the 10-year period 1978–1987 (Johnson, 1978). This projected demand could significantly exceed the supply of newly trained people if mining engineering schools prove to be correct in

forecasting a graduation rate of 375–425 per year for the period 1978–1982 (Johnson, 1978, p. 40) and if this rate does not increase beyond 1982.

Supply–demand relationships in the short-term future can be reckoned along similar lines for graduates in all fields directly related to the mineral industries, albeit with less confidence. The results of both formal and informal surveys suggest that 6000 or more technically trained people, and perhaps many more, will be needed during the coming decade. There is no present assurance that the supply of such people will not fall seriously short, but on this score one at least can express enrollment-based hopes for which there was little or no justification as recently as 10 years ago. Moreover, there is reason to believe that both the growing body of students and the training they receive are improving in average quality. This trend has been noted with satisfaction by a small host of recent employers.

Yet it is necessary to ask about the *top* levels of new talent, about those young people who must provide basic leadership in the future. Are we producing enough people with the intellect and imagination, the interest and drive, the breadth and depth of high-quality training required for vigorous progress toward understanding mineral resources? The answer assuredly is negative, as perhaps it always has been. Efforts to attract more students with exceptional potential, to provide them with superior training, and to motivate them for leadership roles in resource-related areas of science, engineering, and technology must be given a high priority by a large number of educational institutions. A few colleges and universities are making such special efforts, and having success; others should join them.

It is interesting to examine the current attitudes and aspirations of young people who are working toward careers in the mineral industries. According to a recent survey of 1163 students in mining and metallurgical engineering programs (Dresher, 1978), two thirds of them chose their major after entering college. Of the total enrollees, many were influenced in their choice by a relative or a close friend who worked for a mining company. Few were influenced by high-school experiences, by the news media, or by representatives from industry. The major factors of attraction were indicated as challenging work, opportunities for advancement, and prospects for steady employment. Main employment interests were listed as engineering, production, management, and research and development, and only a small fraction of the students indicated an interest in teaching or government service. The situation may well be significantly different among students with a more scientific orientation, but comparable recent surveys in the pertinent areas do not appear to have been made.

The current training of young people for careers related to mineral resources is regarded by some thoughtful observers as adequate to very good, and by others as only fair to good. In most participating institutions it is being vigorously improved and increasingly well coordinated with applied problems. A few critics, however, point out that the training is not well supported by basic research efforts in many of these institutions. More widespread is the complaint that results of basic research, however insufficient, are not yet well enough applied

to recognize practical problems. Nonetheless, traditional college-level requirements in chemistry, physics, and mathematics are being expanded where appropriate; research projects involve increasing number of students; and exposure to courses in the humanities, social sciences, law, and business is growing. Interdisciplinary majors are receiving more encouragement than ever, and it seems clear that at least some institutions are making special efforts to graduate people who are well educated rather than just highly trained. This is a welcome development that is in harmony with ever-increasing needs for a more systemic approach to problems of mineral resources.

Some gaps between academia and the “real world” are being closed with the introduction of work–study programs in cooperation with industry, the increasing use of adjunct professors who bring special expertise to the campus, the broadening participation of university professors in governmental activities, and the development of governmental internship programs for well-qualified students. The students themselves give cause for encouragement, as most are intelligent, well motivated, responsive to trends away from “pure disciplines,” and willing to consider agreements as well as differences of views. They constitute a changing mix of backgrounds and interests, and their ranks are being enlarged by the addition of growing numbers of women, some ethnic minorities, and representatives from other countries.

All this is not to say that our institutions of higher education are without problems. Quality programs that are interdisciplinary or that require both “pure” and “applied” kinds of inquiry can flourish or wane according to the interactions of the professors involved, and the effectiveness of these interactions rests heavily upon mutual respect for contrasting skills, fields of expertise, and points of view. Such effectiveness is not readily attained, but it is easily destroyed. Adequate funding in the face of growing requirements and rising costs also is a troublesome matter in many institutions, and all too commonly there are few or no resources for research projects involving students or for the replacement of obsolete or worn-out equipment. And there are some indications that government support of academic research is increasingly being directed toward larger institutions at the expense of smaller ones (e.g., National Science Board, 1977; Smith and Karlesky, 1977). Even with these and other difficulties, however, our educational institutions seem to be dealing positively with their growing responsibilities.

PROSPECTS FOR THE GRADUATE IN THE MINERAL INDUSTRIES

The present graduate in the mineral industries and related fields has opportunities to make much-needed contributions to knowledge and understanding and to our future well-being. That there is no lack of challenge is clearly indicated by several thoughtful discussions elsewhere in this volume, and in most respects the graduate is qualified to deal with technical challenges.

On the other hand, the graduate also faces a remarkable

range of frustrations. To begin with, he or she will be using a specialized language that is imperfectly understood by others who are less well informed. This and other problems of communication, commonly with responsible people who have different priorities, must be overcome. The graduate also will soon realize that he or she has become involved in a general area that often has had an uncertain or poor public image. He or she is likely to enter an arena in which regulation struggles with competition and in which there have been few discernible basic government policies. He or she may well be discouraged by what appear to be poor perspectives of government agencies and their representatives, by arbitrary decisions founded on incomplete data and imperfect analyses, and by evidence that some decision-makers have not been properly informed on all matters relating to mineral resources. Frustration may be prompted by cost-benefit analyses that reflect preoccupation with some pertinent factors and neglect of others.

Nor will the graduate find public attitudes to be wholly sympathetic, or concerned members of the public to be prepared for useful dialogue. Even though an estimated \$10 billion per year is being spent in handling scientific and technical information (National Science Board, 1977, p. 60), the public remains startlingly uninformed on many important aspects of mineral resources, their exploration and extraction, and their use. It is remarkable, for example, that fewer than half of the people in this country believe that we face an energy shortage, either at present or in the not-distant future. Similar attitudes prevail with respect to mineral resources, and it can be expected that broad public sympathy and support for minerals-oriented programs will not surface until crisis conditions are at hand.

Even so, there are some encouraging signs. The general prestige of people identified with science and technology has improved during the 1970's, according to recent surveys (National Science Board, 1977, pp. 169-182). More than half of those polled evidently believe that science and technology have accomplished more good than harm, although there are some indications of decreasing approval during recent years. Of special significance to the extractive industries are major concerns about the environment. Although science and technology are viewed as having been effective in combating and controlling pollution problems, they are held accountable by a large segment of the public for contributions to environmental damage. At least one can take comfort from an indication that, in 1976, 42 percent of the public believed that science and technology had caused few or none of our current problems. It is sobering, however, to note that an average of less than 30 percent of the public believe that science and technology will solve most of our problems, according to surveys made in 1972, 1974, and 1976.

How can problems of mineral resources be addressed and solved? According to recent recommendations of the National Academy of Sciences and the National Academy of Engineering, increased industrial support should be directed to mineral education, new texts and references should be developed and adopted for college-level curricula, and additional attention should be given to the education of foreign students (even though substantial numbers of such students are currently en-

rolled in mineral-industries curricula). Few will argue with recommendations that there be improved coordination of federal mineral policies and that there be improved media coverage, work-study programs, and other efforts to educate members of the public and government concerning contributions of the mineral industries to our society and economy.

Some of these needs can be identified with a philosophical approach to the problem. There has often been a strong tendency toward tunnel vision on the part of many people, i.e., an insistence on viewing one part of a complex system without considering the others, and an even stronger tendency to lay blame rather than to attack the problem. We seem to be all too readily inclined toward polarization of views, and often neglect areas of common concern. The systems with which we are dealing are much too complicated for casual, out-of-context, or special-interest approaches, a matter on which some penetrating education is desperately needed.

TECHNICAL TRAINING FOR NONTECHNICAL CAREERS

In addition to the output of graduates in mineral-resources fields, there is a widespread need for further education of people who will have responsibilities and influence in nontechnical areas. Little such training can be expected at the high-school level until much more is accomplished at more advanced levels.

One approach, already taken by several colleges and universities, is the addition of required technical courses in nontechnical curricula. To judge from numerous sources, these courses range from exciting and effective to mundane or counterproductive, depending largely on the attitudes and qualifications of the professors who teach them. Some of the courses are team taught, which is expensive but can be highly effective, but most are handled by individual faculty. Ideally, a professor in such a course is well informed in several fields, articulate, and scrupulously fair in presentations of complex issues. He or she ideally treats problems as parts of the wide-ranging systems to which they belong and takes pains to avoid polarization on major issues. Too often, however, the course reflects a particular professor's biases. If team taught, the course often lacks cohesiveness and reflects the immediate interests of each individual professor. Such joint teaching efforts have often failed to achieve the desired objectives. Fortunately, other efforts of this kind have been successful.

Another approach that has been effective in at least two universities is the establishment of an interdisciplinary major with a designation such as "Society and Technology" or "Values, Technology, and Society." In such a major, the student is involved in communications among technical and nontechnical experts; the interplay of science, technology, and public policy; and the difficult problems of equating human values and demands with advances in science and technology. Such curricula require skillful professors who communicate well with one another, who have considerable mutual respect, and who are concerned with maintenance of a well-integrated program.

Perhaps our most immediate need lies in the field of continuing education, in this instance for influential representa-

tives of the news media, public agencies and governing bodies, and the public itself. The most promising avenue for improved education of the public, in the context of mineral resources, probably is represented by key people from the news media, especially journalists with genuine interests in covering technical topics in their work. In one highly successful program at a western university, a carefully selected group of professional journalists has been brought to the campus each year for several weeks of exposure to experts on the academic scene. In effect, this represents an unusual investment in communications, with prospects for large payoffs in improved interchanges with the public. The journalists in this fellowship program have demonstrated a high level of intelligence and interest and a remarkable capacity for raising penetrating questions on all aspects of complex problems.

We would do well to aim at similar programs for key people on the staffs of congressmen, state legislators, and public agencies. Such staffs include persons who are intelligent and highly motivated and who have important responsibilities for recommending mineral policies, regulations, and the funding of pertinent research investigations. Few of them have had training, or have developed real understanding, in major aspects of mineral-resources problems. They are people who should be reached in special programs of continuing education, and many of them doubtless would welcome such opportunities. A familiarity with the technical aspects and complexities of the problems involved with mineral resources would be advantageous for those with the responsibility for drafting regulations and legislation.

CONCLUSIONS

The fundamental limitations on availability of most mineral resources point up a need for improved understanding of their origin and occurrence, along with a marked speed-up in policy development and decision making with respect to their production and uses. To attain such objectives, broad improvements in the educational process are required.

Most promising in essential fields of related education are recent improvements in technical training, along with growing successes in identifying and attracting able minds for careers in resource development. Also recognizable are personal and curricular expressions of closer, more sympathetic coordination between theoretical and applied studies and between technical and nontechnical education. These trends are in the right direction, but they should be stronger and more widely devel-

oped. Further attention should be given to increased involvement of students in first-rate research efforts and to providing more opportunities for scientific and technical continuing education at the graduate level.

The need is critical for more broadly directed kinds of education aimed at present and future policy and decision makers, representatives of the news media, and the voting public, if present interests, attitudes, and apparent levels of understanding are to be taken at face value. Educational institutions should be urged to establish required courses, and even curricula, that give expert integrated attention to the scientific, technical, environmental, social, economic, political, and legal aspects of resources and their uses. Continuing education for key members of the news media and staffs of public officials and government agencies could contribute to significant improvements in the transfer of information so urgently needed.

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APPENDIX

Panel Members—

Brief Biographical Sketches

PAUL B. BARTON, JR., *Chairman*

Geologist, U.S. Geological Survey, Reston, Virginia.

Ph.D., Columbia University (1955). President, Society of Economic Geologists (1979); member, National Academy of Sciences. Specialty: genesis of mineral deposits and chemical and physical nature of ore-forming fluids.

SAMUEL S. ADAMS

Vice-President, Fugro Rocky Mountain, Inc., Boulder, Colorado.

Ph.D., Harvard (1967). Thayer Linsley Lecturer (1978–1979). Specialty: mineral exploration, ore deposit evaluation, and uranium deposits.

PAUL A. BAILLY

President, Occidental Minerals Corp., Lakewood, Colorado.

Ph.D., Stanford (1951). President, Society of Economic Geologists (1981); member, COMRATE—Committee on Mineral Resources and the Environment, National Research Council (1972–1975); chairman, COMRATE Task Force Minerals Policy (1973–1974); member, Advisory Board—Office of Earth Sciences, National Research Council (1977–1980). Specialty: mineral exploration, minerals policy.

HUBERT L. BARNES

Professor of Geochemistry and Director of Ore Deposit Research Section, The Pennsylvania State University.

Ph.D., Columbia (1958). Chairman, U.S. National Committee for Geochemistry (1975–1978). Specialty: geochemistry of hydrothermal ore-forming processes.

C. WAYNE BURNHAM

Professor of Geochemistry and Head, Department of Geosciences, The Pennsylvania State University.

Ph.D., California Institute of Technology (1955). President, Geochemical Society (1974). Specialty: igneous petrology, geochemistry of mineral deposits.

LAWRENCE M. CATHLES III

Associate Professor of Geochemistry, The Pennsylvania State University.

Ph.D., Princeton (1971). Specialty: physics and chemistry of igneous intrusive environments.

HEINRICH D. HOLLAND

Professor of Geochemistry, Harvard University.

Ph.D., Columbia University (1952). President, Geochemical Society (1970–1971); member, National Academy of Sciences. Specialty: chemistry of ore-forming fluids, evolution of the oceans and atmosphere.

JOHN HOWER, JR.

Chairman, Department of Geology, University of Illinois.

Ph.D., Washington University, St. Louis (1955). Director, Geochemistry Program, National Science Foundation (1976–1978). Specialty: petrology and geochemistry of sediments and clay mineralogy.

RICHARD H. JAHNS

Professor of Geology and Dean, School of Earth Sciences, Stanford University.

Ph.D., California Institute of Technology (1943). President, Geological Society of America (1970–1971). Specialty: economic geology and igneous and metamorphic geology.

ANTHONY J. NALDRETT

Professor of Geology, University of Toronto.

Ph.D., Queen's University (1964). Fellow, Royal Society of Canada; editor, *Journal of Petrology* (1973 to present). Specialty: magmatic ore deposits.

HIROSHI OHMOTO

Professor of Geochemistry, The Pennsylvania State University.

Ph.D., Princeton (1969). Specialty: isotopic geochemistry of ore-forming fluids.

SAM H. PATTERSON

Geologist, U.S. Geological Survey, Reston, Virginia.

Ph.D., University of Illinois (1955). Specialty: economic geology of bauxite, other aluminum resources, and clays (kaolin, refractory clay, bentonite, and fuller's earth).

ULRICH PETERSEN

Professor of Geology, Harvard University.

Ph.D., Harvard (1963). Chief Geologist, Cerro de Pasco Corporation (1957–1963); Order of Merit for Distinguished Service from the Government of Peru. Specialty: mineral genesis and zoning in hydrothermal ore deposits.

OMER B. RAUP

Geologist, U.S. Geological Survey, Denver, Colorado.

Ph.D., University of Colorado (1962). Specialty: marine evaporites, sedimentary mineral deposits.

ARTHUR W. ROSE

Professor of Geochemistry, The Pennsylvania State University.

Ph.D., California Institute of Technology (1958). Senior Geologist, Kennecott Copper Corporation (1958–1964); Mining Geologist, State of Alaska (1964–1967); President, Association of Exploration Geochemists (1980–1981). Specialty: Geochemical exploration and economic geochemistry of metals.

RICHARD P. SHELDON

Geologist, U.S. Geological Survey, Reston, Virginia.

Ph.D., Stanford (1956). Chief Geologist, U.S. Geological Survey (1972–1977). Specialty: sedimentary mineral deposits, particularly phosphate.

STEWART R. WALLACE

Consultant, Lakewood, Colorado.

Ph.D., University of Michigan (1953). Chief Geologist, Climax Molybdenum Corporation (1955–1969); AIME Jackling Lecturer (1974); Vice-President, Society of Economic Geologists (1978). Specialty: Geology and origin of porphyry–stockwork deposits, particularly molybdenum.

DAVID H. WATKINSON

Professor of Geology, Carleton University, Ottawa, Canada.

Ph.D., The Pennsylvania State University (1965). Specialty: Mineral deposits and igneous rocks in Precambrian terrain.